Does movement matter? Exploring the relationship between lumbo-pelvic movement and back pain using wireless inertial motion sensors

Robert A Laird

B Sci (Physio), Post Grad Manip Physio, Post Grad Sports Physio

A thesis submitted for the degree of Doctor of Philosophy at Monash University in 2018

Department of Physiotherapy

Faculty of Medicine Nursing and Health Sciences

Copyright notice

© Laird 2018. Except as provided in the Copyright Act 1968, this thesis may not be reproduced in any form without the written permission of the author.

I certify that I have made all reasonable efforts to secure copyright permissions for third-party content included in this thesis and have not knowingly added copyright content to my work without the owner's permission.

Table of Contents

Abstract

Background

Low back pain (LBP) has been a leading cause of global disability over the last three decades. Despite over 30 years of research, there is still considerable uncertainty about why persistent LBP develops in some people but not in others. Although movement-related interventions have been recommended by most international guidelines for LBP management, there is a lack of clarity or direction as to which type of intervention is best or how to identify which individuals might be more responsive to a specific type of intervention. This is, at least in part, because the role and relevance of movement to the development, treatment and prevention of LBP remain unclear. This thesis examines the role of lumbo-pelvic movement and its association with LBP in people with and without persistent (> 3months) LBP.

Method

Two systematic reviews (published papers 1 and 2) were initially conducted to identify what was known about the effectiveness of movement interventions, and if movement-related differences existed in people with and without LBP. Three studies (papers 3 (published), 4 (under minor revision) and 5 (under revision) report the use of wireless inertial motion and electromyographic sensors to measure and compare lumbo-pelvic kinematic differences in people with and without persistent LBP. The first empirical study (n=63) tested the consistency and reliability of lumbo-pelvic kinematic measurements. The second study (n=266) described the flexion-related lumbo-pelvic kinematic parameters, defined typical and atypical movement, and used univariate analysis to compare the prevalence of atypical movement between people with and without persistent LBP. The third empirical investigation tested the same cohort (n=266) for patterns in flexion-related lumbo-pelvic kinematic parameters using latent class analysis.

Results

The two reviews identified that (i) movement interventions inconsistently changed movement and that changes in movement showed little association with any change in pain or activity limitation, and (ii) people with persistent LBP had smaller lumbar range of movement (ROM) in sagittal, frontal and axial planes, slower movement speed and reduced proprioception accuracy than people without LBP. The first empirical study showed good to excellent agreement between testers and reported the bandwidth that represented expected movement variation for each parameter. The second study found that the LBP group had a significantly higher prevalence of atypically small trunk, lumbar and pelvic ROM, slower movement, delayed pelvic movement and loss of flexion relaxation than the group without LBP. The third empirical study found four distinct subgroups of lumbo-pelvic kinematic patterns with an unequal distribution among people with and without LBP.

Conclusions
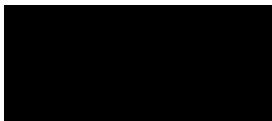
People with persistent LBP move differently to those without persistent LBP. By using wireless motion and EMG sensors, atypical movement(s) can be identified in individuals with LBP, however there is wide variation of the type and size of atypical movement. If only a percentage of the LBP population have atypical movements, then

Doctoral Thesis – Robert A Laird

knowledge of the type and magnitude of atypical movement parameter(s) would be important if clinicians or researchers are to observe any relationship between atypical movement and LBP. The presence of four flexion-related movement patterns highlights the movement-based heterogeneity of people with persistent LBP. The presence of subgroups based on lumbo-pelvic kinematics also has significant implications for both management and future research. It is logical that distinctly different movement-based subgroups may have differing magnitudes and/or directions of responses to interventions. This heterogeneity may contribute to inconsistent results seen in trials of interventions for LBP.

Doctoral Thesis – Robert A Laird

General Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Signature:

Print name: Robert Laird

Date: 16/8/18

Thesis including published works declaration

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

This thesis includes three original papers published in peer-reviewed journals and two submitted publications, as detailed in the following table of publications in the thesis (p.11-12). The thesis describes an exploration of the relationship between lumbo-pelvic movement and pain through movement analysis in those with and without back pain using wireless inertial motion and surface electromyographic sensors. The ideas, development and writing of all the papers in this thesis were the principal responsibility of myself, as a PhD student, working within the Faculty of Medicine, Nursing and Health Sciences, under the supervision of Emeritus Professor Jenny Keating, and Associate Professor Peter Kent.

The inclusion of co-authors reflects the fact that the work came from active collaboration between researchers and acknowledges input into team-based research. I have renumbered sections and reformatted the referencing style of published or submitted papers to generate a consistent presentation as well as a consolidated reference list within the thesis.

Student signature: ████████████████████████ Date: 8/8/2018

The undersigned hereby certifies that the above declaration correctly reflects the nature and extent of the student's and co-authors' contributions to this work. In instances where I am not the responsible author, I have consulted with the responsible author to agree on their respective contributions of the authors.

Main supervisor signature: █████████████████████ Date: 8/8/2018

Table of publications in thesis

Thesis Chapter & section	Publication title	Publication status	Nature and % of student contribution	Co-author name(s) and % of co-author's contribution	Co-author(s) Monash student Y/N
2.2	Modifying patterns of movement in people with persistent LBP – does it help? A systematic review	Published BMC Musculoskeletal Disorders 2012 **13**:169	Contributed to the conceptualisation, review of literature, drafting and preparing for publication; 80%	Professor Jennifer Keating contributed to conception, data analysis, draft and review; 10% Associate Professor Peter Kent contributed to data extraction, draft and review; 10%	N
3.2	Comparing lumbo-pelvic kinematics in people with and without persistent LBP: a systematic review and meta-analysis	Published BMC Musculoskeletal Disorders *2014 **15**:229*	Contributed to the conceptualisation, review of literature, drafting and preparing for publication; 75%	Professor Jennifer Keating contributed to conception, data analysis, draft and review; 10%. Associate Professor Peter Kent contributed to conception, draft and review 7.5%. Mr Jayce Gilbert contributed to data extraction and review 7.5%	N
4.2	How consistent are lordosis, range of movement and lumbo-pelvic rhythm (LPR) in people with and without back pain?	Published BMC Musculoskeletal Disorders *2016 **17**:403*	Led the conception of the study and data collection, led data analysis & synthesis, drafted and prepared the manuscript for publication; 80%	Professor Jennifer Keating contributed to conception, draft data analysis and review; 10% Associate Professor Peter Kent contributed to conception, data analysis, draft and review; 10%	N
5.2	Does movement matter in people with back pain? Investigating 'atypical' lumbo-pelvic	*Submitted to* BMC Musculoskeletal Disorders	Led the conception of the study and data collection, led data analysis & synthesis, drafted	Professor Jennifer Keating contributed to conception, draft data analysis and review; 7.5% Associate Professor Peter Kent contributed to	N

	kinematics in people with and without back pain using wireless movement sensors		and prepared the manuscript for publication; 75%	conception, data analysis, draft and review; 7.5% Mr Kasper Ussing contributed to data collection and review; 5% Ms Paoline Li contributed to data collection, data extraction and review; 5%	
6.2	Are there patterns in the lumbo-pelvic flexion kinematics of people with and without persistent LBP?	*Submitted to* BMC Musculoskeletal Disorders	Led the conception of the study and data collection, led data analysis & synthesis, drafted and prepared the manuscript for publication; 80%	Professor Jennifer Keating contributed to conception, draft and review; 10% Associate Professor Peter Kent contributed to data analysis, draft and review; 10%	N

Acknowledgements

For a man who was neither a writer nor researcher, this completed thesis stands on the shoulders of a few brave and foolhardy people who helped reveal the deep mysteries of statistics, research and authorship.

To Professor Jennifer Keating, I will always be indebted to you for your patient persistence, deep statistical knowledge, fierce intellectual rigour and optimistic encouragement. My first attempts at writing anything must have made you deeply doubt the wisdom of accepting me as a PhD student. I will be sending you a packet of red ink pens to replace the many that you exhausted while reviewing my work. This thesis would not have been possible without you.

To Professor Peter Kent, thank you for your sustained encouragement, friendship, and guidance. Your knowledge of the world of low back pain research, your insight into statistical processes and your willingness to guide this work, shone a bright light that helped navigate and straighten the PhD pathway.

To Suzanne Capell, thank you for your important assistance in proof reading as well as your generous hospitality.

> *"Perpetual devotion to what a man calls his business, is only to be sustained by perpetual neglect of many other things."* (Robert Louis Stevenson).

There are a few other people who are owed special recognition. To Paoline Li, thank you for your contribution to this research, and allowing me the space and opportunity to pursue research goals while maintaining a clinical role. To my children (Jessica, Ben, James and Nathan) and wider family, thank you for your encouragement and patience.

And lastly, to my wife Gwen, who was my anchor at the beginning, the middle and the end, …, your love and friendship kept me afloat and heading in the right direction through turbulent seas and calm waters alike.

☦

Oral presentations by candidate

Oral presentations

Laird, R., Kent, P., & Keating, J. (2011). Modifying patterns of movement in people with low back pain - does it help? A systematic review. Paper presented at Australian Physiotherapy Association Biennial Conference, Brisbane Conference Centre, Brisbane, 27th -30th October, 2011

Laird, R., de Graaff, S., & Haines, T., (2013). Improving back pain with motion sensing technology. Paper and practical demonstration presented at Australian Pain Society, 3rs Annual Scientific meeting, National Convention Centre, Canberra, Australia, 17-20th March, 2013.

List of publications

Publications by candidate incorporated into thesis:

Published

Laird, R., Kent, P., & Keating, J. (2012). "Modifying patterns of movement in people with low back pain - does it help? A systematic review." BMC Musculoskeletal Disorders **13**: 169.

Laird, R., Gilbert, J., Kent, P., & Keating, J. (2014). "Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis." BMC Musculoskeletal Disorders **15**(1): 229.

Laird, R., Kent, P., & Keating, J. (2016). "How consistent are lordosis, range of movement and lumbo-pelvic rhythm in people with and without back pain?" BMC Musculoskeletal Disorders **17**: 403.

In press

Laird, R., Kent, P., & Keating, J. (2018B) Subgroups of lumbo-pelvic flexion kinematics are present in people with and without persistent LBP?

Under review

Laird, R., Ussing, K., Li P., Kent, P., & Keating, J. (2018A), Does movement matter in people with back pain? Investigating 'atypical' lumbo-pelvic kinematics in people with and without back pain using wireless movement sensors.

List of tables

List of figures

1. Introduction: does movement matter for people with low back pain?

1.1. An overview of this thesis

This thesis presents the work associated with five papers - two systematic reviews and three empirical investigations - that report explorations of the relationships between movement and persistent low back pain (LBP) of greater than 3 months duration. In combination, these papers provide a systematic exploration of lumbo-pelvic movement in people with and without persistent LBP. Figure 1.1 outlines the flow of the thesis.

Paper 1: Modifying movement patterns in people with low back pain - does it help? A systematic review

Paper 2: Comparing lumbo-pelvic movement in people with and without persistent LBP: A systematic review and meta-anlysis

Paper 3: How consistent are lordosis, range of motion and lumbo-pelvic rhythm in people with and without persistent LBP?

Paper 4: Investigating 'atypical' lumbo-pelvic kinematics in people with and without back pain using wireless movement sensors

Paper 5: There are subgroups of lumbo-pelvic flexion kinematics in people with and without back pain

Table 1.1: The sequence of papers contained within this thesis

The work opens with a systematic review that analysed clinical trials of interventions designed to modify patterns of movement in people presenting with back pain. The primary questions related to this review were whether interventions could change movement patterns, and if so, whether changes to movement patterns were related to changes in pain and/or activity limitation. Despite the popularity of movement-related interventions for people with persistent LBP, this review found only a small number of randomised clinical trials that measured both treatment outcomes and changes in movement pattern parameters. Those trials that did measure movement pattern parameters identified small, inconsistent changes in movement parameters associated with interventions, and little evidence of a relationship between changes in movement patterns and changes in pain or activity limitation.

The second study in this thesis was a systematic review of studies that compared lumbo-pelvic kinematics of people with and without persistent LBP using non-invasive (skin-surface) measurement techniques. Extracted data were used to summarise the lumbo-pelvic parameters that had been studied and to describe similarities and differences between those with and without back pain. The conclusions of the second review were that, on average, people with persistent LBP have a smaller lumbar range of movement (ROM), reduced proprioception and slower movement speed. That review also highlighted the heterogeneous nature of available studies with respect to method design and quality.

The third publication in this thesis examined the consistency (measurement stability/repeatability) and reliability of three types of lumbo-pelvic kinematic parameters. Measurements were taken using wireless motion and electromyography sensors in 63 people with and without persistent LBP. The results indicated good tester reliability and potentially sufficient movement consistency for clinical use of most measurements.

The fourth paper describes kinematic parameters of lumbo-pelvic flexion and sitting in a sample of 266 people with and without persistent LBP using the same wireless motion and EMG sensors. A method for conceptualising 'atypical' movement was argued and defined. Using the 10th and 90th centiles of the measurements for people without persistent LBP (NoLBP) as criterion thresholds for 'atypical' movement, the prevalence of atypical flexion-related lumbo-pelvic kinematic parameters in the NoLBP and LBP groups was compared. Differences in the prevalence of atypical movement were observed for the parameters of ROM, timing of specific movements and speed of movement, but not for lumbo-pelvic rhythm or for any sitting parameter.

The fifth and final paper in this thesis describes the use of multivariable analysis to examine if patterns (subgroups) of flexion-related lumbo-pelvic kinematics are evident in data for this sample of 266 people with and without persistent LBP. A four-subgroup model fitted the data best, with differences seen in the proportion of those with and without persistent LBP belonging to each subgroup. People without persistent LBP mostly belonged to one subgroup with a smaller distribution to two other subgroups, while people with persistent LBP were present in all four subgroups.

1.1.1. Thesis summary

This thesis builds an argument for the clinical relevance of analysis of lumbo-pelvic movement in the assessment and treatment of LBP. While treatment based on movement patterns has been advocated in the past, this thesis provides the first evidence of LBP-related movement subgroups based solely on multivariate analysis of direct measurements of movement parameters. This work provides a model for ongoing research with the potential to better understand biomechanical adaptations associated with back pain. The results of these studies also support the concept that, while movement is affected in many people with persistent LBP, there are distinctly different ways in which movement is affected. The results create a reason to question whether movement-based treatments should be indiscriminately prescribed to a non-stratified group of people with persistent LBP, or whether interventions could be strategically matched to specific, individually identified, atypical patterns of movement. The work of this thesis shows that such matching appears possible and could inform future empirical investigations comparing non-specific treatment with treatment that addresses observed movement characteristics.

1.2. Background

1.2.1. Definition of persistent LBP

LBP presents as pain located between the ribs and gluteal creases (lumbar region). It may be accompanied by unilateral or bilateral leg pain with or without neurological symptoms (Dionne, CE et al., 2008). Pain that persists for longer than 3 months may be classified as chronic or persistent pain (Treede, R et al., 2015). Hartvigsen et al. (2018) note that LBP is a symptom rather than a disease and is generally categorised into specific and non-specific diagnoses. The specific and non-specific diagnoses have been categorised into (1) spinal disorders

with serious or systemic pathology, (2) spinal pain with neurological deficits, (3) non-specific spinal pain and (4) spinal pain from non-spinal sources (Haldeman, S et al., 2012).

1.2.2. Epidemiology of persistent LBP

LBP is both common and costly to communities around the world. Different metrics have been used to describe its impact, but all indicate that LBP is a distressing problem that is becoming increasingly prevalent. When combined with neck pain, it was defined as "the leading [global] cause of activity limitation" in 2016, based on analysis of 'years lived with activity limitation' (Vos, T et al., 2017, p. 1229) The global prevalence of LBP has steadily increased over the last 30 years. In 1990, back and neck pain was rated the 12th highest cause of global 'activity limitation adjusted life years'[1], rising to 8th in 2005 and to 4th in 2015 (Vos, T et al., 2016a, p. 1554). The global point prevalence of 'activity-limiting' LBP was recently reported to be 7.3% (Vos, T et al., 2016b). In Australia in 2015, LBP was the most common musculoskeletal reason for seeing a general medical practitioner and was reported to affect over 3.7 million Australians (Britt, H et al., 2016). Sixteen percent of Australians reported LBP of >6months duration in 2015 (AIHW, 2016), confirming the high prevalence and persistence of LBP in Australian society.

Reports on the incidence of the 'first-ever' episode of LBP in a one-year period range from 6.3% (Biering-Sorensen, F, 1984a) to 15.4% (Croft, P et al., 1999; Hoy, D et al., 2010). The rate of recurrence varies with definition (Marras, W et al., 2007; Stanton, TR et al., 2009). Hestbaek et al. (2003) systematically reviewed the long-term course of LBP and reported that 62% (95%CI 42-75%) of people who reported an initial back pain episode still had pain after 12 months, with 60% of people (95%CI 44-78%) reporting recurrent episodes. The authors concluded that the risk of further LBP was twice as high for those with previous LBP compared with those without a previous episode. In a study of 1172 Australians with acute LBP, 75% reported that they had experienced a previous episode (Henschke, N et al., 2009). The concept that non-specific LBP is trivial, benign and 'self-limiting' (Indahl, A et al., 1995; Waddell, G., 1996) is not reflected in its widespread and escalating prevalence or patterns of recurrence.

---

[1] Activity limitation/disability adjusted life years (DALYs) is a metric that combines the metrics of years lived with activity limitation (YLDs) and years of life lost (YLLs)

The impact of back pain on the individual and the broader community is significant. Based on Australian data from 2008-2009, back-related problems accounted for 1.8% (AUD $1.2 billion) of the total government health care expenditure and estimates of indirect costs (including physiotherapy and over-the-counter medicines) were calculated to be around AUD $4.8 billion at that time (AIHW, 2016). Costs in the United States were reported to be as much as USD $80.1billion in 2005 (Martin, BI et al., 2008). The economic and personal impact of chronic LBP is also reflected in its association with reduced participation in employment. Schofield et al. (2012, p. 1156) reported that in 2008-2009, "41% of Australians aged between 45-64 years who identify chronic LBP as their main health problem are not in the workforce". While other co-morbidities are likely to be present, this statistic provides an indication of the negative effects of chronic LBP on work, income and lifestyle.

At an individual and personal level, psychological and social factors can contribute to a loss of well-being. Froud et al. (2014) systematically reviewed the impact of chronic LBP at an individual level. They identified a wide range of negative factors, such as loss of function, damaged interpersonal and work-related relationships, loss of employment, stigma (reduced credibility and negative beliefs from others about the legitimacy of back pain) and negative psychological factors such as increased anxiety, depression, anger and frustration.

1.2.3.   Persistent LBP is a multidimensional problem

In the late 1970s and early 1980s, the increasing prevalence of LBP, and the failure of interventions to adequately deal with LBP, challenged researchers and clinicians to look beyond a biomedical explanation of LBP and to include a broader bio-psycho-social perspective (Engel, GL, 1977; Waddell, G, 1987). Since that time, there has been a significant body of research that confirms a strong association between psychosocial factors and LBP (Adams, N, 2006; Govindu, NK et al., 2014; Iles, RA et al., 2008; Kato, K et al., 2017; Mielenz, TJ et al., 2008; Mitchell, T et al., 2009; Yang, H et al., 2016). As such, the term 'biopsychosocial' has been used as a framework to consider the diverse factors associated with LBP persistence. Within the biopsychosocial context, factors that have been associated with LBP include:

(i)   patho-anatomy (i.e. disc degeneration and prolapse (Adams, MA et al., 2012; Ohtori, S et al., 2015; Rajasekaran, S et al., 2013; van Heeswijk, V et al., 2017; Wade, K et al., 2014), spinal canal stenosis (Watters, W et al., 2008; Weinstein, J et al., 2008), spondylolisthesis

(Niggemann, P et al., 2011) and other non-spinal sources of pain such as neoplasm, infection, fracture and metabolic disease,

(ii)   cognitions (e.g. beliefs that movement will cause damage) (Bunzli, S et al., 2015; Rabey, M et al., 2016),

(iii)   emotions, such as fear (Caneiro, JP et al., 2017; Serbic, DM et al., 2014),

(iv)   pain behaviour and pain types (Rabey, M et al., 2016),

(v)   societal circumstances (Yang, H et al., 2016) and lifestyle (i.e. smoking, alcohol consumption and BMI) (Goldberg, MS et al., 2000; Govindu, NK et al., 2014; Kaila-Kangas, L et al., 2003; Schmelzer, A et al., 2016; van Heeswijk, V et al., 2017), and

(vi)   lumbo-pelvic movement and postural elements (Bhattacharya, A et al., 2009; Haugstad, G et al., 2006b; Hodges, P et al., 2013; Hodges, P et al., 2009; Kent, P et al., 2015a; Marras, WS et al., 1999a; Marras, WS et al., 1993b; O'Sullivan, P. B., 2005; Ogurkowska, MB et al., 2013; Shum, G et al., 2005; Tsang, S et al., 2017; Vaisy, MP et al., 2015).

Persistent LBP is complex

The multidimensional biopsychosocial nature of persistent LBP introduces complexity into clinical assessment, as varying contributions from a range of dimensions may be present for each individual. This complexity is compounded by the considerable variety in parameters seen within each dimension. For example, emotional contributors might include differing levels of fear, anger, sadness and/or frustration; lifestyle issues might include geographical constraints for medical services, smoking and alcohol consumption and/or an inability to drive. Similarly, a wide range of altered movement and posture-related parameters have been associated with LBP.

1.2.4.   Why examine lumbo-pelvic movement?

This thesis focuses on the dimension of lumbo-pelvic movement using the commonly accepted Cartesian system for assessing movement. Measurements of physiological and physical attributes are required to distinguish between normal and abnormal human function (i.e. blood pressure, heart rate, body mass, blood oxygen, glucose or cholesterol levels etc). Measuring movement-related functions is also of interest for a range

of reasons, such as improving occupational efficiency, reducing injury risk, facilitating sports-related functions, determining movement deficits where they may relate to injury prevention, and monitoring recovery from injury.

If any aspect of biopsychosocial function is associated with persistent LBP, some form of measurement is required to understand how it might contribute to pain and activity limitation. Measuring the frequency and magnitude of parameters, within any dimension, that are thought to be associated with pain will help to clarify the nature of that relationship. Measuring any changes to parameters as a result of an intervention can then provide insight into whether those parameters might be the cause (or consequence) of pain and/or activity limitation.

Assessment of lumbo-pelvic kinematics is commonly included in the clinical assessment of people with persistent LBP, in the belief that improving lumbo-pelvic movement will also be associated with improvements in pain and activity limitation. This belief has its origins in the large body of evidence on the therapeutic advantages of using movement to reduce pain and activity limitation following injury and disease. For example, 30 minutes of daily, moderate intensity exercise is recommended in people with cardiovascular disease (Briffa, T et al., 2006). In the musculoskeletal context, strength training following hip fracture improves gait and balance (Sherrington, C et al., 1997); strength and mobility training are recommended by international guidelines to improve pain and activity limitation in people with knee osteoarthritis (Bartholdy, C et al., 2017; McAlindon, TE et al., 2014); resistance training is recommended in people with osteoporosis (Russo, C, 2009); and combinations of mobility and strength exercises are typically used following fracture. It follows logically that therapeutic movement-related interventions to restore normal movement in people with persistent LBP should lead to improvements in pain and activity limitation. However, although most national guidelines recommend exercise for people with persistent LBP as a first-line strategy (Koes, B et al., 2010; NICE, 2016), there is general recognition that there is uncertainty about which type of exercise is best. In addition, only relatively modest benefits of most exercise strategies have been demonstrated in group averages from intervention studies (Hayden, J et al., 2011).

1.2.5. Lumbo-pelvic movement parameters and their association with pain

A wide range of movement parameters have been associated with persistent LBP. Altered movement-related parameters include reduced proprioception (Georgy, E, 2011b; Gill, K et al., 1998; Koumantakis, G. A. et al.,

2002; Tong, MH et al., 2017), reduced lumbar extension strength (Mayer, J et al., 2008; Pranata, A et al., 2017; Steele, J et al., 2014), reduced balance (Iversen, MD et al., 2009; Jacobs, JV et al., 2011; Maribo, T et al., 2012), reduced lumbar ROM (Marras, WS et al., 1995b; McGregor, AH et al., 1997), altered movement and muscle activation patterns (Richardson, C, 1997; Richardson, C et al., 1999), sub-optimal postures in sitting and standing (Dankaerts, W. et al., 2006a; Dankaerts, W. et al., 2006e; Jain, S et al., 2005) and altered breathing mechanics (Hamaoui, A et al., 2002; Kolar, P et al., 2012; McLaughlin, L et al., 2011; Roussel, N et al., 2009).

Pain alters movement

There is a clear association between pain, activity limitation and altered movement, however, the nature and strength of this relationship in the case of LBP is less clear. It has been shown that injury-related pain typically affects movement. Experimental pain studies confirm that movement parameters and patterns change in the presence of pain (Castelein, B et al., 2017; Shiozawa, S et al., 2015; van den Hoorn, W et al., 2015). When LBP is experimentally induced in people without a history of LBP, movement parameters and patterns alter. For example, using hypertonic saline injections into interspinous ligaments, Wong et al. (2016) reported an increase in trunk stiffness with increased lumbar extensor and anterior abdominal muscle activity. Other studies using similar techniques report reduced pressure pain thresholds, and reduced ability to actively perform a straight leg raise when supine (Palsson, T et al., 2015; Schilder, A et al., 2014). Noxious heat applied to the L5 spinous process was associated with significant increases in lumbar extensor muscle activity and altered lumbo-pelvic rhythm (Dubois, J et al., 2011). Changes to lumbar sway and lumbar muscle forces have also been seen in experimentally induced pain, with a reduction in the lumbar motion that is typically associated with breathing, i.e. motion is reduced during the pain period and is greater prior to and after pain induction (Smith, M et al., 2005). Greater variability of isometric force production is seen during the artificially induced pain period when people are asked to exert 50% and 75% of maximal isometric flexion and extension thoraco-lumbar spine torque (Descarreaux, M et al., 2005a). These experiments all indicate that the presence of pain can alter lumbo-pelvic movement parameters in people who do not have LBP.

Movement may contribute to pain

There is also evidence that movement may cause injury and pain. Finite modelling of lumbo-sacral biomechanics and anatomical studies consistently report disc damage and failure with repeated flexion (bending) and rotation (Berger-Roscher, N et al., 2016; Heeswijk, V et al., 2017; Wade, K et al., 2014). Increases

in load have also been associated with reduced disc nutrition, annular failure, inflammation and endplate defects (Arun, RDMM et al., 2009; Miyagi, MMD et al., 2012; Mulholland, R, 2008; Rodriguez-Soto, A et al., 2013)). Research into risk factors for the onset of LBP include evidence of an association with flexion activities, repetitive lifting and longer work duration (Coenen, P et al., 2013; Kawaguchi, M et al., 2017; Ramond-Roquin, A et al., 2015; Taylor, JB et al., 2014). There is also a strong belief about this association in the community, with a study of the views of clinicians and patients showing an endorsement of biomechanical factors as the most important risk factor category including lifting, bending and prolonged sitting (Stevens, M et al., 2016).

1.3.   Does changing movement parameters improve LBP?

Despite the large body of research on movement-related parameters over the last few decades, it is surprising that there is still little agreement about the cause-versus-consequence relationship of movement behaviours with LBP. Research and the development of clinical theory into movement parameters has contributed to the creation of interventions aimed at specifically addressing aberrant movement. For example, delayed onset of transversus abdominis, atrophy of multifidus and increased activation of superficial erector spinae and oblique abdominal muscles led to the concept of improving 'core stability' through a series of stabilising exercises. However, despite large numbers of randomised controlled trials, there is still considerable uncertainty about the merit of specific types of exercise compared with general exercise for people with persistent LBP. It could be argued that movement-related parameters are less influential in persistent LBP than psychosocial drivers. However, despite 25 years of continued research and the gradual acceptance of a biopsychosocial model, the prevalence of persistent LBP continues to increase (Vos, T et al., 2016b). A recent systematic review of nine trials of the effectiveness of multidisciplinary biopsychosocial interventions for people with sub-acute LBP found benefit when compared with usual (minimal) treatment but little difference when compared with other types of interventions (Marin, TJ et al., 2017) .The authors also determined that available research is of low to very low quality and that additional high-quality evidence is required to better evaluate the utility of a biopsychosocial approach. Nevertheless, when all available evidence is considered, Marin et al. reported low- to very low-quality evidence that biopsychosocial interventions are similar in effect to "*a brief intervention with features from a light mobilization program and a graded activity program, functional restoration, brief clinical intervention including education and advice on exercise, and psychological counselling*".

In summary, clarity is currently lacking about the role of interventions that are implemented to change movement parameters in order to reduce LBP. We do not know whether these interventions can change movements or if such changes to movement are accompanied by improvements in pain and/or activity limitation.

This thesis focuses on lumbo-pelvic movement in people with and without persistent LBP, and aims to (i) review the evidence of a relationship between changes in movement patterns and changes in pain and activity limitation following any intervention for persistent LBP, (ii) review evidence of what is known about differences in lumbo-pelvic kinematics between people with and without LBP, (iii) test and compare the consistency in lumbo-pelvic movement and posture in people with and without LBP, (iv) define and test the prevalence of atypical movement in people with and without LBP, and (v) investigate patterns in lumbo-pelvic movement parameters for people with and without LBP.

2. Chapter 2 – Do movement patterns change with interventions?

2.1. Introduction

2.1.1. Movement interventions are popular for treating LBP

There are many types of interventions designed to reduce persistent LBP. Some interventions are general in nature e.g. advice to 'stay active' (Indahl, A et al., 1995) or doing a general exercise program, while others are very specific, such as lumbar extension strength exercises, acupuncture or massage. Within the dimension of movement, there are widely divergent movement-related intervention strategies for improving pain. For instance, Indahl et al. (1995) compared an advice-only intervention (explaining the importance of staying active by doing normal activities of daily living) with no treatment, based on the hypothesis that people with persistent LBP had *excessive muscular stabilisation* arising from fear of movement and re-injury. This approach contrasts with interventions based on beliefs that there *is insufficient muscular stabilisation* (Hodges, P et al., 1996) where treatment aims to increase muscular stabilisation of spinal structures. Other movement-related interventions include strategies to increase ROM (Maitland, G, 1986), use directionally specific movement (McKenzie, R, 1987), or change movement and muscle activation patterns (O'Sullivan, P. B., 2005; Richardson, C et al., 1999; Sahrmann, S, 2002a).

Given the wide range of movement-related intervention types, it is not surprising that trials of non-invasive interventions for persisting LBP have reported varied results. The recently published NICE guidelines on evidence for non-invasive treatments for persistent LBP, (NICE, 2016, p. 305) was based on the review of 75 randomised trials that compared exercise interventions and concluded *"…. that there was some evidence of benefit for all exercise types compared to usual care or other active comparators, but no clear evidence for one type being superior to another and benefits were seen inconsistently across critical outcomes."* Outcomes considered in the guidelines included health-related quality of life, pain severity, function and psychological distress, but no analysis of relationships between physical changes and changes in pain, activity limitation or any psychological outcome.

2.1.2. Interventions that target patterns of movement to improve LBP

There is a variety of popular interventions that aim to improve pain and function by changing a pattern of movement that is thought to be associated with LBP. Strategies to improve 'core stability' (Hodges, PW, 2003; Marshall, PW et al., 2011), improve postural parameters (Jain, S et al., 2005; Meziat Filho, N et al., 2015; Shirazi-Adl, A et al., 1996; Troyanovich, SJ et al., 1998) and identify/modify maladaptive movement patterns (O'Sullivan, P. B., 2005; Sahrmann, S, 2002a) have all been proposed as therapeutic interventions to improve pain and function in people with persistent LBP.

Systematic reviews prior to 2011 (Ferreira, P et al., 2006; Hauggaard, A et al., 2007; Macedo, LG et al., 2009; Rackwitz, B et al., 2006) that assessed interventions related to core stability theories using motor control exercise (also known as stabilisation exercise) on trunk and abdominal muscle activation patterns arrived at similar conclusions to those reported in the NICE guidelines. Collectively, these reviews on motor control exercises included 26 randomised controlled trials on stabilisation-type exercise interventions. Ferreira (Ferreira, P et al., 2006) reviewed 13 trials (three included in a meta-analysis) of the effect of stabilisation exercises on persistent LBP of greater than 3 months duration. They concluded that stabilisation exercises were more effective than usual care (defined as advice and education) in reducing pain and activity limitation in people with LBP of more than 3 months duration. Rackwitz et al. (2006) pooled data from five trials in a meta-analysis and reached a similar conclusion but noted that stabilisation exercises were not necessarily any better than general exercise. Macedo et al. (2009) included 14 motor control exercise intervention trials for people with persistent LBP and concluded that motor control exercise was superior to minimal or no treatment but was not superior to other forms of treatment such as manual therapy or general exercise. Aligned with the NICE guidelines, these reviews reported pain-related and activity limitation-related outcomes but did not examine if the trials changed the targeted muscle activation or movement patterns, or if any movement-related changes were related to changes in activity limitation or pain measurements.

There is limited evidence that targeting specific interventions to individuals and/or subgroups based on various biopsychosocial parameters offers better outcomes (Asenlof, Denison et al. 2005, Fersum, O'Sullivan et al. 2012, Kent, Laird et al. 2015, Hahne, Ford et al. 2017). However, there is little evidence that supports targeting specific kinematic parameters improves outcomes. It is not known whether a change to any particular movement parameter is associated with a change in pain or activity limitation. Improvements in pain and activity limitation

might occur without a corresponding change in any movement parameter, or alternately, changes might occur in a targeted movement pattern or parameter without change in pain or activity limitation. It is conceivable that LBP might arise from causes other than the targeted movement patterns. Changes to pain or activity limitation could occur through other mechanisms such as the patient-therapist relationship, a change in cognitions e.g. reducing fear avoidance, and/or general encouragement to move. If an intervention is targeted to a specific movement pattern or parameter, then it is important to know if the targeted parameter changed, and if changes in the target are associated with changes in pain or activity limitation.

Therefore, a systematic review was conducted to investigate what was known (prior to 2011) from clinical trials about changes to any movement patterns following interventions for persistent LBP and the relationship between changes in movement and changes in pain and activity limitation. The review 'Modifying patterns of movement in people with persistent LBP – does it help? A systematic review' was published In BMC Musculoskeletal Disorders (ranked in the 2nd quartile of the Web of Science, Journal citation reports, Orthopaedics category with an impact factor of 1.998) and is reproduced in this chapter. It has been viewed 11,529 times and cited 14 times. The following section (2.2) is an identical Word document version of the published article, reproduced within the thesis to enable higher-quality text, suitable for printing if required. The published PDF version (see Figure 2.1) can be seen in Appendix A and an electronic copy of the PDF is available via open access at: https://bmcmusculoskeletdisord.biomedcentral.com/articles/10.1186/1471-2474-13-169

Laird *et al. BMC Musculoskeletal Disorders* 2012, **13**:169
http://www.biomedcentral.com/1471-2474/13/169

BMC
Musculoskeletal Disorders

RESEARCH ARTICLE   **Open Access**

Modifying patterns of movement in people with low back pain – does it help? A systematic review

Robert A Laird[1,3*], Peter Kent[2] and Jennifer L Keating[1]
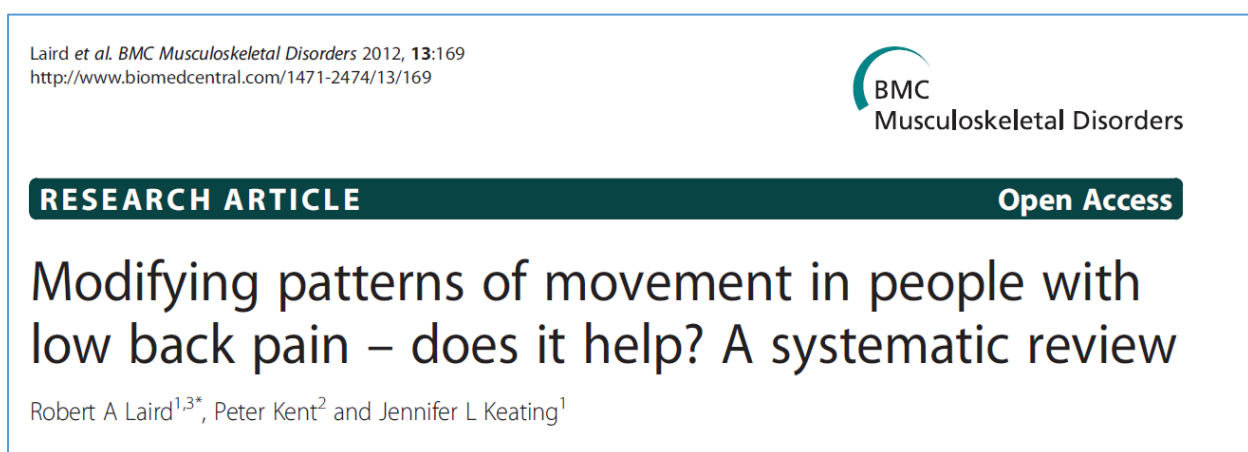
Figure 2.1 The PDF version of this paper is available in Appendix A

2.2. Modifying patterns of movement in people with low back pain – does it help? A systematic review

Robert A Laird, PT[1], Peter Kent, PhD[2], Jennifer L Keating, PhD[1]

[1]Department of Physiotherapy, Monash University, Frankston, Victoria, Australia

[2]Research Department, Spine Centre of Southern Denmark, Lillibaelt Hospital, Institute of Regional Health Services Research, University of Southern Denmark, Middelfart, Denmark

Corresponding author: Robert Laird

Department of Physiotherapy, Monash University, ███████████████████████████████

███████████████████████████████████

███████████████████████████████████

Email addresses:

███████████████████████

███████████████████████████

███████████████████████

2.2.1.   Abstract

Background

Physiotherapy for people with low back pain frequently includes assessment and modification of lumbo-pelvic movement. Interventions commonly aim to restore normal movement and thereby reduce pain and improve activity limitation. The objective of this systematic review was to investigate: (i) the effect of movement-based interventions on movement patterns (muscle activation, lumbo-pelvic kinematics or postural patterns) of people with low back pain (LBP), and (ii) the relationship between changes in movement patterns and subsequent changes in pain and activity limitation.

Methods

MEDLINE, Cochrane Central, EMBASE, AMI, CINAHL, Scopus, AMED, ISI Web of Science were searched from inception until January 2012. Randomised controlled trials or controlled clinical trials of people with LBP were eligible for inclusion. The intervention must have been designed to influence (i) muscle activity patterns, (ii) lumbo-pelvic kinematic patterns or (iii) postural patterns and included measurement of such deficits before and after treatment, to allow determination of the success of the intervention on the lumbo-pelvic movement. Twelve trials (25% of retrieved studies) met the inclusion criteria. Two reviewers independently identified, assessed and extracted data. The PEDro scale was used to assess method quality. Intervention effects were described using standardised differences between group means and 95% confidence intervals.

Results

The included trials showed inconsistent, mostly small to moderate intervention effects on targeted movement patterns. There was considerable heterogeneity in trial design, intervention type and outcome measures. A relationship between changes to movement patterns and improvements in pain or activity limitation was observed in one of six studies on muscle activation patterns, one of four studies that examined the flexion relaxation response pattern and in two of three studies that assessed lumbo-pelvic kinematics or postural characteristics.

Conclusions

Movement-based interventions were infrequently effective for changing observable movement patterns. A relationship between changes in movement patterns and improvement in pain or activity

limitation was also infrequently observed. No independent studies confirm any observed relationships. Challenges for future research include defining best methods for measuring (i) movement aberrations, (ii) improvements in movements, and (iii) the relationship between changes in how people move and associated changes in other health indicators such as activity limitation.

Key words: low back pain, movement disorders, randomized controlled trial, exercise therapy, posture

2.2.2. Background

The causes of low back pain (LBP) appear to be complex and multifactorial, with both biological and psychosocial components associated with chronicity (Waddell, G, 1996; Weiner, BK, 2008). While numerous patho-anatomic structures have been associated with LBP, it is often difficult to establish a definitive anatomical cause or initiating factor for LBP in individual people (Kent, P et al., 2005; Koes, B, van Tulder, M., and Thomas, S, 2006). Furthermore, although the pathogenesis of LBP has also been associated with genetic causes (Battié, MC et al., 2009), such influences are not readily modifiable. In daily practice, many clinicians observe and treat physical impairments ranging from postural anomalies (Scannell, J et al., 2003; Smith, A et al., 2008), localised intervertebral kinetic disturbance (Teyhen, DS et al., 2007), motor control disturbance (Hodges, P et al., 1996; Hodges, P et al., 2009), muscle imbalance (Lee, J et al., 1999) and muscle atrophy (Hides, J et al., 1996).

People with persistent (chronic) or recurrent LBP have been variably reported to exhibit movement pattern aberrations such as increased trunk stiffness (Hodges, P et al., 2009; Van Daele, U et al., 2010), poor proprioception (Descarreaux, M et al., 2005b), altered patterns of activation of abdominal muscles (Hodges, P et al., 1996; Silfies, SP et al., 2009b), extensor muscles (Hides, J et al., 2008; Hides, JA et al., 2001; Wallwork, TL et al., 2009), and postural dysfunction (Dunk, NM et al., 2010; Gregory, DE et al., 2008; Williams, MM et al., 1991). Different patterns of lumbo-pelvic kinematics during activities such as forward bending and sit-to-stand have been demonstrated in studies comparing people with and without LBP (Esola, MA et al., 1996; McClure, PW et al., 1997; Shum, GL et al., 2007; Silfies, SP et al., 2009a). Methods for measuring lumbo-pelvic movement patterns can by categorised into three broad target groups: (i) muscle activity patterns, for example the contribution of deep versus superficial trunk muscles, (ii) patterns of hip to lumbar kinematics, for example the relative contributions of hip joint

compared with lumbar spine movement to specific activities such as forward bending or walking, and (iii) postural patterns, for example slumped sitting compared with upright sitting posture.

Numerous interventions have targeted movement pattern aberrations associated with chronic LBP (Bryan, M et al., 2003; Hodges, P et al., 1996; McKenzie, R et al., 2003a; Richardson, C et al., 1999; Van Dillen, LR et al., 2003). Some exercise interventions involve whole body movements such as aerobic exercise, Pilates, and yoga, while others target the activity of specific muscles. The effectiveness of exercise for LBP appears modest and not consistently associated with any particular form of exercise (Slade, SC et al., 2006; Slade, SC et al., 2007; van Middelkoop, M et al., 2010). No consistent differences in LBP outcomes have been observed for highly individualised exercise programs that aim to alter lumbo-pelvic kinematics or postural patterns such as those based on the Alexander Technique (Ernst, E et al., 2003; Little, P et al., 2008a), the Feldenkrais Method (Ernst, E et al., 2003) or Pilates (Lim, E et al., 2011) compared with non-specific exercise. Similarly, reviews of interventions designed to alter patterns of specific muscle activity, variably described as motor control, trunk stabilisation or core stabilising exercise, have concluded little difference between outcomes achieved with motor control exercise compared with general exercise regimens (Ferreira, P et al., 2006; Hauggaard, A et al., 2007; Macedo, LG et al., 2009; May, S et al., 2008; Rackwitz, B et al., 2006). As there is no standardisation in the reporting of exercise type, intensity, duration or frequency, one possibility is that some exercises are effective, but when trial outcomes are pooled, method heterogeneity in included studies precludes identification of trial-specific effectiveness.

Movement pattern aberrations associated with LBP, such as deviation from the normal activation patterns of Transversus Abdominus (TA) (Ferreira, PH et al., 2004; Hodges, P et al., 1996) have been reported. However, the effect of interventions on these aberrant movement deficits has not been systematically evaluated. While most trials report effects on pain or activity limitation, few have measured changes in movement or postural patterns. This is reflected in five recent systematic reviews on the effectiveness of stabilisation ('motor control') exercises for LBP (Ferreira, P et al., 2006; Hauggaard, A et al., 2007; Macedo, LG et al., 2009; May, S et al., 2008; Rackwitz, B et al., 2006), which collectively synthesised 26 randomised controlled trials. More than half of the included trials in these reviews (Ferreira, P et al., 2006; Hauggaard, A et al., 2007; Macedo, LG et al., 2009; May, S et al., 2008; Rackwitz, B et al., 2006) used outcome measures of pain and activity limitation without measurement of any movement characteristic. Only three of 26 trials measured the effect of the

intervention on a specific movement pattern aberration. As few trials measure movement pattern aberrations, this leaves three fundamental questions unanswered by existing reviews: (i) were movement pattern aberrations actually present in trial participants who received interventions designed to remedy these deficits? (ii) did the intervention achieve the intention of changing the movement pattern? and (iii) were improvements in other health parameters such as pain and activity limitation related to changes in movements classified as aberrant? To understand whether treatment can change movement pattern aberration, measurement of such deficits should occur before and after treatment, and the outcomes compared with those of a control group.

Aims of this review

The first aim of this systematic review was to determine the effect of movement-based interventions on movement patterns defined as physical measures of muscle activation, lumbo-pelvic kinematics or postural patterns in adults with LBP. The second aim was to examine the relationship between changes in movement patterns and subsequent changes in pain and activity limitation.

2.2.3.   Methods

Data Sources

Eight electronic databases (MEDLINE, Cochrane CENTRAL, EMBASE, AMI, CINAHL, Scopus, AMED, ISI Web of Science) were searched from inception until January 2012 using a sensitive search strategy based on that recommended by the Cochrane Collaboration (see appendix E for sample search strategy). The search yield was initially screened for eligibility by one reviewer (RL) on title and abstract to remove duplicates and clearly unrelated articles. A more detailed screening on title and abstract, and subsequently on retrieved full text articles, was performed independently by two reviewers (RL and PK). Disagreements were resolved by discussion. The protocol for this review has not previously been registered or published.

Study Selection: Inclusion and exclusion criteria

Trials were included if they were randomised controlled trials or controlled clinical trials that only contained participants with lumbo-pelvic pain (+/- leg pain) in both the intervention and control groups. The intervention must have been specifically designed to influence any one of three observable patterns of movement: (i) muscle activity patterns, (ii) lumbo-pelvic kinematic patterns or (iii) postural patterns.

To be as inclusive as possible, no restrictions were placed on the duration of complaint or pain location. Full inclusion details of each study are provided in Appendix A. Exclusion criteria were trials of animals, of drug interventions and trials that included people who were pregnant or had spinal malignancy, infection, fracture, cauda equina syndrome, metabolic or spinal inflammatory disorders.

Types of outcome measures

For trials to be included, pre- and post-intervention data that quantified baseline measures and the effect on the target movement pattern relative to control measurements must have been reported. In the absence of these data, it could not be determined if the intervention was effective in changing the physical parameter it was designed to influence. These data were also required to investigate the relationship between change in movement patterns and change in health outcomes (pain and activity limitation). Acceptable methods for assessing movement patterns included any measures of specific muscle activation (e.g. timing of contraction, cross-sectional area, muscle thickness, electromyographic activity, ultrasound or other imaging measurement), lumbo-pelvic kinematics (eg a change in sequence, timing or coordination of movements such as lumbar versus hip contribution during lifting, sit-to-stand, forward bending) and any measures of sustained positions/postures of the lumbo-pelvic region (eg analysis of spinal kinematics within specified activities such as standing, sitting or sustained bending). Data must have been provided that described movement patterns (e.g. hip versus lumbar range, deep versus superficial muscle activity, particular sequences of timing, electrical activity or movement etc.).

Exclusion criteria at the level of outcome type were trials with outcomes that described only global ROM or global measures of strength (e.g. trunk extension range or strength only), or trials that did not include data that enabled estimates of change in pain or activity limitation. This was because we considered that global range or strength were not surrogate measures of how the body coordinates movement patterns.

Data Extraction

From all included papers, two assessors independently extracted the following data: compliance with review inclusion criteria, type and duration of intervention for experimental and comparison groups, number and type of participants, the targeted movement characteristic (muscle activity pattern, lumbo-pelvic kinematic pattern or postural pattern), pre- and post-intervention outcome measurements and their method of measurement. Data extracted by these reviewers (RL and PK) were checked for

concordance and where differences occurred, a third reviewer (JK) cross-checked data with consensus reached by discussion.

Assessment of method quality

The PEDro scale was applied to assess potential sources of bias in included studies (Verhagen, AP et al., 1998). The PEDro scale has been reported as being adequately reliable (Maher, CG et al., 2003) and valid (de Morton, N, 2009). Each clinical trial with a quality rating score on the PEDro website (http://www.pedro.org.au) has been independently assessed by two raters trained to assess method quality. Therefore, where available, we used the quality scores from the PEDro website for included trials. There were two trials (reported in three papers) where scores were not available (da Fonseca, JL et al., 2009; Unsgaard-Tondel, M et al., 2010; Vasseljen, O et al., 2010) and these were independently assessed (RL and PK) using the same PEDro scale and decision rules.

Data Synthesis and Analysis

Study details (inclusion/exclusion criteria, intervention and comparison treatments and outcome measure details) were extracted and summarized (see Appendix B). Means and standard deviations (SDs) for intervention and control groups, for each comparison, at each reported outcome period and for all three categories of outcome variables (movement pattern, pain, activity limitation) were entered into Revman (v5) software ("Review Manager (RevMan) ", 2008). This software was used to calculate standardised mean differences (SMD) between intervention and comparison groups. Negative values for SMDs indicated outcomes in favour of the experimental group.

2.2.4.   Results

Search yield

The search identified 9288 potentially relevant articles and 24 other articles were identified through other sources. Following screening of title and abstract, 47 articles were retrieved in full text. Twelve trials (16 articles) met the inclusion criteria for this review (Akbari, A et al., 2008b; da Fonseca, JL et al., 2009; Freeman, MD et al., 2010; Haugstad, GK et al., 2008; Hides, J et al., 1996; Hides, JA et al., 2001; Lalanne, K et al., 2009; Magnusson, ML et al., 2008; Mannion, AF et al., 1999a; Mannion, AF et al., 2001b; Marshall, P et al., 2008; O'Sullivan, P et al., 1998; O'Sullivan, P et al., 1997; Ritvanen, T et al., 2007; Unsgaard-Tondel, M et al., 2010; Vasseljen, O et al., 2010; Vasseljen, O et al., 2012). Most

of them examined a range of physical outcome measures, however only data on patterns of muscle activity, lumbo-pelvic kinematics or posture patterns (as well as pain and activity scores) were extracted. A flow diagram of the study selection process is shown in Figure 2.2. The trials retrieved in full text and subsequently excluded are listed in Appendix C, together with reasons for their exclusion. Details of included studies are detailed in Appendix B. The wide variety of interventions and physical measures in the included trials prevented pooling in a meta-analysis.
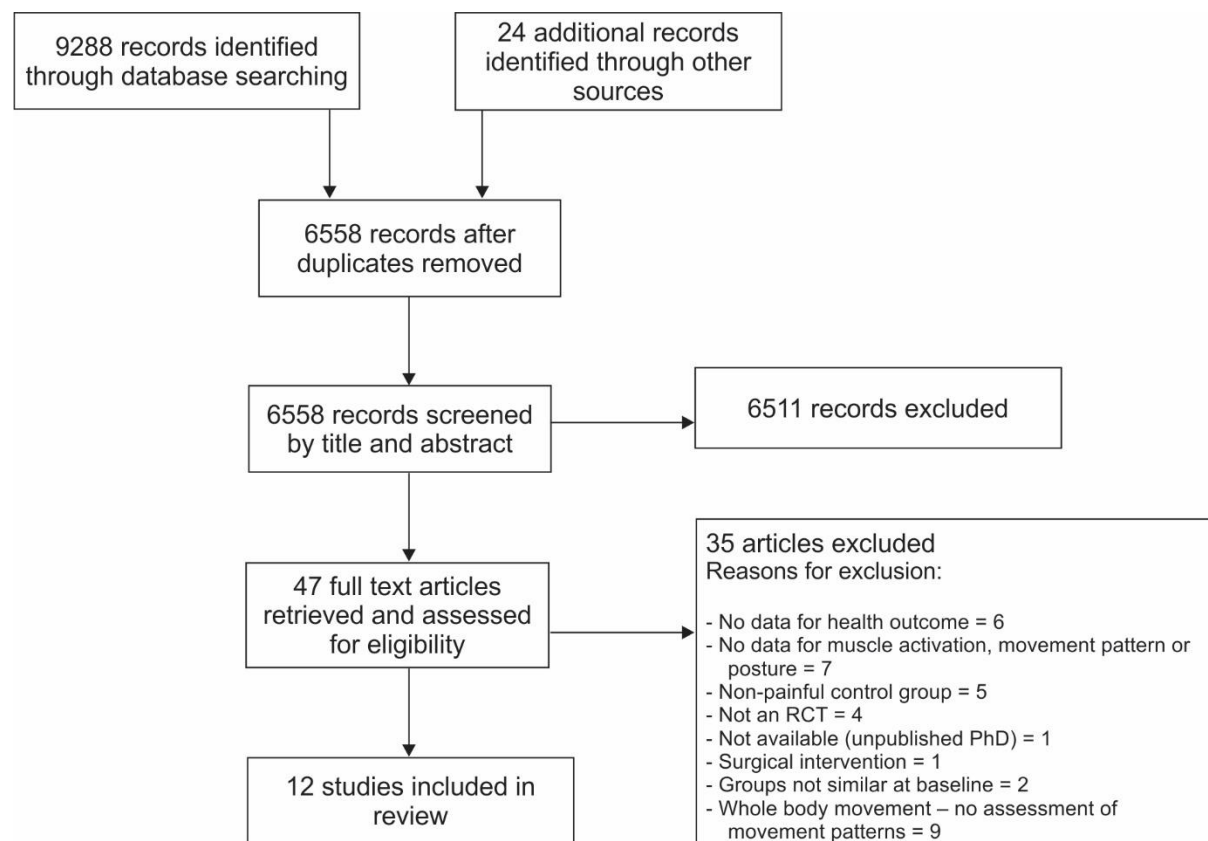
Figure 2.2 Flow diagram of study selection

Quality assessment

The method quality of the included trials is shown in Table 2.1. No trial included blinding of therapists or participants. This is not surprising, given how difficult this is to achieve in exercise or movement intervention trials. On the 0-10 quality scale, the mean score of included trials was 5.6 (range 3 to 8).

Table 2.1 Quality assessment of included studies

PEDro criteria*	Akbari 2008	Da Fonesca 2009	Ferreira 2010	Haugstad 2006	Hides 1996&2001	Lalanne 2009	Magnussen 2008	Mannion 1999&2001	Marshall 2008	O'Sullivan 1997&1998	Ritaven 2007	Vasseljen 2010, 2012 & Unsgaard-Tonsel 2010
1. Eligibility criteria were specified	✓	✓	X	✓	✓	X	✓	✓	✓	✓	✓	✓
2. Random allocation of subjects	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3. Allocation was concealed	X	X	X	X	✓	X	X	X	X	✓	✓	✓
4. Groups similar at baseline	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
5. There was blinding of all subjects	X	X	X	X	X	X	X	X	X	X	X	X
6. Blinding of therapists	X	X	X	✓	X	X	X	X	X	X	X	X
7. Blinding of assessors	✓	X	✓	✓	✓	X	X	X	X	✓	✓	✓
8. >1 key outcome was obtained for more than 85% of subjects initially allocated to groups	X	✓	✓	X	✓	X	X	✓	✓	✓	✓	✓
9. All subjects ... received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analysed by 'intention to treat'	X	✓	X	X	X	X	X	X	X	X	X	✓
10. The results of between-group statistical comparisons are reported for at least one key outcome	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
11. The study provides both point measures and measures of variability for at least one key outcome	X	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓
Total score	4	5	6	6	7	4	3	5	5	7	7	8
Assessor	PEDro	RL &PK	PEDro	PEDro	PEDro	PEDro	PEDro	PEDro	PEDro	PEDro	PEDro	RL &PK

Item one is not included as part of the 10 point PEDro scoring

Types of trials found

Movement patterns measured by the included trials were classified into three arbitrary groups that measured: (i) specific trunk muscle activity patterns, (ii) 'flexion relaxation response' changes and (iii) various aspects of lumbo-pelvic kinematics and postural patterns. To focus the reporting, the analysis of results and the discussion were anchored to these three groups. Ten trials recruited people with chronic pain (> 3 months), one recruited people with both acute and chronic pain, and one recruited people with pain for less than three weeks (see Table 2.2 and Appendix B).

Trials measuring muscle activity patterns - intervention effects

Six of the 12 trials examined effects of interventions on specific muscle activity. Five trials compared motor control exercise, as described by Richardson et al (1999), with general exercise (Akbari, A et al., 2008b; Hides, J et al., 1996; O'Sullivan, P et al., 1998; O'Sullivan, P et al., 1997; Vasseljen, O et al., 2010) and one trial compared Swiss ball exercise to general exercise (Marshall, P et al., 2008). Nine different outcome measures of muscle activity patterns were measured across the six trials and included TA thickness, TA movement, Lumbar Multifidus (LM) thickness, onset of contraction of the deep abdominal wall muscles and ratios of muscle activity.

Five trials (see Table 2.3) included outcomes related to specific muscle activity patterns with one trial showing a statistically significant difference between experimental and comparison groups for changes to TA thickness (Ferreira, P et al., 2010) and another trial reporting a significant difference in the ratio of TA to Rectus Abdominus (RA) activity during double leg raise. (O'Sullivan, P et al., 1998). No differences between groups were seen for TA movement (Vasseljen, O et al., 2010) or deep abdominal wall muscle feed-forward timing (Marshall, P et al., 2008; Vasseljen, O et al., 2012). Ferreira et al (2010) (Quality Assessment (QA) score 6/10) found significant (ANCOVA-adjusted) differences between groups in TA thickness ratio (contraction versus resting thickness) favouring motor control exercise compared with either spinal manipulative therapy or general exercise. Effects adjusted for baseline differences were: MCE vs GE 12% greater improvement (p=0.043); MCE vs SMT 11.4% (p=0.053). Unadjusted post-intervention differences between groups were not significant; SMDs: MCE vs SMT -0.70 (-0.42 to 0.12); MCE vs GE -0.29 (-0.44 to 0.57). O'Sullivan et al (1997) (QA 7/10) found a significant increase in the ratio of deep (TA and Internal Oblique) to superficial abdominal wall muscle

Table 2.2 Summary of main categories of movement pattern investigated in the included studies

Type of pattern		Author	Components of movement pattern assessed								Measurement details		Health outcomes	
			TA thickness	TA slide	TA+IO timing	LM thickness	Ratio muscle	FRR	Movement	Posture	Method of measurement	Characteristics of movement pattern measured	Pain	Activity limitation
Muscle activation patterns	Specific muscle activity	**Akbari 2008** *Motor control vs general exercise*	✓			✓					Ultrasound	Muscle size - thickness at rest (mm)	✓	
		Hides 1996 & 2001 *Motor control exercise vs medical treatment*				✓					Ultrasound	Muscle size – cross sectional area (mm^2)	✓	
		Ferreira 2010 motor control exercise vs general ex vs spinal manipulative therapy	✓								Ultrasound	Muscle thickness - % change from resting thickness	✓	✓
		Marshall 2008 *Swiss ball vs general exercise*			✓						Surface EMG	Feed forward activation	✓	✓
		O'Sullivan 1997 *Motor control vs GP management*					✓				Surface EMG	Internal Oblique and Rectus Abdominus electrical acitivity & ratio	✓	✓
		Vasseljen 2010, 2012 & Unsgaard-Tonsel 2010 *Motor control (low load) vs motor control (high load) vs general exercise*		✓			✓				Ultrasound	Size of muscle on contraction vs size of muscle at rest (ratio), Lateral slide (mm)	✓	✓
	Flexion relaxation response	**Lalanne 2009** *Manipulation vs manual therapy*						✓	✓		Surface EMG and Optoelectronic recording	Angle and intensity of onset and cessation of electrical activity	✓	✓
		Mannion 1999 & 2001 *Physiotherapy vs aerobics vs devices*						✓			Surface EMG	Intensity, onset and cessation of electrical activity	✓	✓
		Marshall 2008 *Swiss ball vs general exercise*						✓			Surface EMG	Intensity, onset and cessation of electrical activity	✓	✓
		Ritvanen 2007 *Traditional bone setting vs physiotherapy*						✓			Surface EMG	Intensity, onset and cessation of electrical activity	✓	✓
Movement patterns		**Da Fonesca 2009** *Pilates vs no Pilates control*							✓		Force plate and treadmill	Gait related forces and rates	✓	
		Magnusson 2008 *Postural biofeedback vs standardized rehab*							✓		Triaxial computerised goniometer	Circumduction area and velocity	✓	✓

Postural patterns		Haugstad 2006 & 2008 *Mensendieck therapy vs standard gynaelogical treatment*								✓	Visual observation	Posture, upper and lower limb movement, gait, sitting posture and respiration	✓	✓

Table 2.3 Summary of results for studies that investigated intervention effects on muscle activity patterns (specific muscle activity)

Study and intervention type (experimental vs comparison)	No. of Subjects	TA thickness	TA slide*	TA & IO feedfoward timing	Multifidus (LM) thickness	Ratio of specific muscle activity	Baseline differences between groups?	SMD and 95%CIs (negative values favour experimental/motor control group)	Pain	Activity	SMD and 95%CIs (negative values favour experimental group)
Akbari 2008 *Motor control exercise vs general exercise*	49	**No**			**No**		No (TA & LM) Pain: Yes‡ Activity: Yes‡	Multifidus thickness -0.21 (-0.74 to 0.33) TA thickness -0.30 (-0.86 to 0.26)	**Yes‡**	**Yes‡**	Pain -1.06 (-1.66 to -0.46) Activity -0.70 (-1.27 to -0.12)
Hides 1996 *Motor control exercise vs control*	39			Yes†,∥			Insufficient data	Insufficient data	No†	No†	Insufficient data
Ferreira 2010 *Motor control exercise(MCE) vs general ex (GE) vs spinal manipulative therapy (SMT)*	**34**					Yes††	**No**	TA thickness ratio (contraction vs rest) MCE vs GE -0.29 (-0.44 to 0.57)†† MCE vs SMT -0.70 (-0.42 to 0.12)††	**No**	**No**	**Pain** -0.32 (-0.44 to 0.54) MCE vs GE -0.51 (-0.42 to 0.30) MCE vs SMT **Activity** -0.25 (-1.11 to 0.61) MCE vs GE -0.63 (-0.42 to 0.19) MCE vs SMT
Marshall 2008 *Swiss ball vs general exercise*	50			**No**			No	Right feedforward activation of TA + IO -0.77 (-1.59 to 0.04) Left feedforward activation of TA+IO -0.46 (-1.25 to 0.34)	No¶	Yes	Activity -0.77 (-1.34 to -0.19)
O'Sullivan 1997 *Motor control exercise vs general exercise*	44					**Yes**	No	Ratio of TA+IO to RA -0.84 (-1.47 to -0.21)	Yes	No**	Pain -1.29 (-1.96 to -0.62) Activity -0.56 (-1.18 to 0.06)

Vasseljen 2010, 2012 & Unsgaard-Tonsel 2010 *Motor control (ultrasound guided exercise (US)) vs motor control (high load, sling exercise (SE)) vs general exercise (GE)*	109	No	No		No	No[§]	TA slide[*] 0.47 (-0.18 to 0.75) TA thickness ratio (contraction vs rest)[#]: TA 0.16 (-0.53 to 0.85) US vs GE IO 0.13 (-0.55 to 0.80) US vs GE EO 0.23 (-0.48 to 0.95) US vs GE TA feedforward timing:[§§] Minimal or no effect size for most comparisons No significant feedforward differences of clinical relevance	No	No	**Pain** -0.46 (-1.09 to 0.18) US vs GE -0.28 (-0.90 to 0.35) US vs SE **Activity** -0.54 (-1.16 to 0.10) US vs GE-0.34 -0.98 to 0.30-0.01) US vs SE

TA = Transversus Abdominus, LM = Lumbar Multifidus, EO = External Oblique, IO = Internal Oblique.

* TA slide = amount of distance (mm) lateral translation of musculotendinous junction present on contraction vs relaxation.

† As reported by the authors, but insufficient data for verification.

‡ Our calculations show a statistically significant difference between groups for pain and activity, however the groups showed a significant difference at baseline which diminishes the strength of any conclusion about relative effectiveness of the intervention.

§ No difference between groups at baseline was noted with the following exceptions: Left versus right differences were noted for the ultrasound guided group for IO ratio and TA lateral slide which created a statistically significant decrease in slide distance (reduced activation) and IO ratio post intervention for the left side only.

|| A statistically significant increase in favour of the experimental group for % size of Multifidus was reported by authors but insufficient data for verification.

¶ Pain data obtained from Marshall 2008b, p331-332.

 # Data for US versus SE groups similar.

**Our calculations of p value differ from those reported in the study, where we calculate p=0.076 for post intervention activity levels (difference between groups post intervention) whereas the study reports p<0.0001. However, the six-month post intervention scores do reach significance (SMD= -0.73, 95%CI -1.35 to -0.11, p=0.021).

†† Authors present ANOVA data (F2,31 = 4.09; p=0.026) in favour of MCE vs GE (p=0.043) and vs SMT (p=0.053).

§§ Side to side differences (nondominant versus dominant side) produced significant, small between-group differences favouring the SE group for the dominant side only (SEvs MCE and SEvs GE) after adjusting for baseline difference.

(Rectus Abdominus) EMG activity favouring the motor control group over general exercise (SMD = -0.84, 95%CI -1.47 to -0.21, p=0.01). Hides et al (1996) (QA 7/10) reported a significant increase in Multifidus size for the motor control group compared with a medical management group but did not provide data suitable for the calculation of effect sizes. Where significant differences between groups were found, effect sizes favouring specific muscle activity (see Table 2.3) were small to moderate (-0.20 to -0.47), with the exception of effects observed by O'Sullivan et al.

Trials measuring muscle activity patterns - relationship between changes in muscle activity and changes in pain or activity levels

Three trials found statistically significant differences between intervention and comparison groups for pain or activity limitation. Marshall et al (2008) (QA 5/10) found no effects for measures of muscle activation but a large effect for activity limitation (but not pain) in favour of the Swiss ball group (SMD=-0.77, 95%CI -1.34 to -0.19, p=0.06). Akbari et al (2008b) (QA 4/10) compared motor control exercise to general exercise and found no significant difference between groups for TA or LM thickness but reported a positive effect for pain (SMD=-1.06, 95%CI -1.66 to -0.46, p=0.00) and activity limitation (SMD=-0.71, 95%CI -1.28 to -0.12, p=0.02) favouring the motor control exercise group. The treatment and comparison groups in the Akbari et al study were significantly different at baseline (the motor control exercise group had less pain and activity limitation at baseline), confounding interpretation of intervention effects on pain and activity levels. Hides et al (2001) reported a significant difference for LM size for the motor control group when compared with the control group but no differences for pain or activity limitation. O'Sullivan et al (1998; 1997) reported a difference between groups favouring motor control exercise for a movement pattern characteristic (ratio of deep to superficial abdominal muscle activity) and also for pain (SMD=-1.29, 95%CI -1.96 to-0.62, p=0.00).

Trials measuring the flexion relaxation response - intervention effects

Four trials examined the muscle activation pattern known as the 'flexion relaxation response' (FRR) (Lalanne, K et al., 2009; Mannion, AF et al., 1999a; Marshall, P et al., 2008; Ritvanen, T et al., 2007). This refers to the electrical silence in lumbar extensors during full flexion typical of people without LBP; people with chronic LBP performing the same movement frequently exhibit continued electrical activity (Geisser, ME et al., 2005; Neblett, R et al., 2003). The FRR is a ratio where the numerator is electrical activity, measured by surface electromyography (EMG) of lumbar extensors while moving from standing

to full flexion and back to standing and the denominator is EMG activity in the fully flexed position (Watson, P et al., 1997). The ratio is largest in those without LBP where a normal finding would be minimal EMG activity in full flexion.

Lalanne et al (2009) (QA 4/10) compared FRR measured during a single session for people with chronic LBP who received manipulation compared with sham manipulation. They reported a significant improvement favouring the manipulation group (SMD=-1.40, 95%CI -2.24 to -0.56, p=0.00). Marshall et al (2008) showed a significant difference in FRR favouring Swiss ball exercise over general exercise (SMD=-1.60 95%CI -2.25 to -0.94, p=0.00). Mannion et al (1999A) (QA 5/10) compared three interventions: (i) a 12-week physiotherapy group (advice, sub-maximal exercise, general strengthening, electrotherapy, heat or cold therapy, but not manual therapy), (ii) a strength training group (using devices), and (iii) an aerobics/stretching group. They found no post-intervention differences for FRR. Ritvanen et al (2007) (QA 7/10) evaluated the effects of traditional bone setting (a whole-body manual therapy approach) compared with physiotherapy (massage, exercise and stretching) and found no significant post-intervention differences for FRR.

Trials measuring the FRR - the relationship between changes to muscle activity patterns and changes to pain or activity level

No trials reporting effects on FRR found differences between groups for pain (Table 2.4). Marshall et al (2008) reported an improvement in FRR (SMD= -0.77, 95%CI -1.34 to -0.19, p=0.01) and improvement in activity levels both favouring Swiss ball exercise over general exercise.

Trials measuring lumbo-pelvic kinematics and postural patterns – intervention effects

Three trials examined intervention effects on lumbo-pelvic kinematic and/or postural patterns. Measurement methods included computerised triaxial inertial goniometry (Magnusson, ML et al., 2008), treadmill with a force platform (de Fonseca, JL et al., 2009) and visual estimation from video image recording. Haugstad et al (2008) (QA 6/10) compared Mensendieck therapy (described as a somato-cognitive movement-based therapy) with medical management for women with chronic non-specific pelvic pain. They reported significant improvement in favour of the experimental group on various physical movement and postural parameters (sitting posture and respiration post-intervention, gait and movement at 12 months) with SMDs ranging from -1.64 to -0.89 (p=0.00 to 0.004).

Magnusson et al (2008) (QA 3/10) compared postural biofeedback with a 'standard rehabilitation program' in people with chronic non-specific LBP and reported a significant increase in lumbo-pelvic circumduction area but did not provide the data required to estimate effect sizes. Da Fonesca et al (2009) (QA 5/10) compared Pilates exercise with a no treatment group in a small number (n=17) of people with chronic non-specific LBP, and found no difference between groups for gait-related parameters.

Trials measuring lumbo-pelvic kinematics and postural patterns – relationship between changes in kinematic and postural patterns, and pain or activity levels

Haugstad et al (2008) reported large effects favouring Mensendieck therapy over medical management for a number of movement parameters (see Table 2.5) and pain (SMD = -1.71, 95%CI -2.46 to -0.97, p=0.00). Magnusson et al (2008) reported an effect favouring postural biofeedback over a 'standard rehabilitation program' for movement (Table 2.5), pain (SMD= -3.60, 95%CI -4.5 to -2.6, p=0.00) and activity limitation (SMD = -0.97, 95%CI -0.43 to -0.12, p=0.00). DaFonesca et a (2009) found no post-intervention difference between groups for physical parameters or pain

Table 2.4 Summary of results for studies that investigated intervention effects on the flexion relaxation response (FRR)

Muscle activity patterns of FRR (electrical patterns of activity in extensor muscles during flexion and return from flexion)								
(Standardised mean difference and 95% confidence intervals, negative values favour experimental group)								
Study and intervention type	Study details		Movement pattern Was there a statistically significant difference (p>0.05) in physical parameters *between* groups?				Health outcomes Was there a statistically significant difference (p<0.05) in health outcomes between groups?	
	No. of subjects	Baseline differences between groups?	FRR* Upper lumbar (T12-L3/4)	FRR* Lower lumbar (L4-S1)	Angle of onset and cessation for FRR	Extension vs flexion EMG ratio	Pain	Activity
Lalanne 2009‡ *Manipulation vs sham*	27	No	**Yes** ↑ -1.40 (-2.24, -0.56)	**No**	**No**	Not measured	**No**	Not measured
Mannion 1999 & 2001 *Physiotherapy vs aerobics* *Physiotherapy vs device strength training*	99	No	**No** [†] *Insufficient data*	**No** [†] *Insufficient data*	Not measured	Not measured	**No**	**No**
Marshall 2008 *Swiss ball vs general exercise*	50	No	**No**	**Yes** ↑ FRR in favour of intervention group -1.60 (-2.25, -0.94)	Not measured	Not measured	**No**	**Yes** Activity -0.77 (-1.34 to -0.19)
Ritvanen 2007 *Traditional bone setting vs physiotherapy*	61	(Intervention group had right vs left differences pre and post treatment)	**No**	**No** (both groups showed ↓ FRR post intervention	Not measured	**No** Trend towards increase for both groups	**No**	**No**

* FRR=Flexion relaxation ratio (the amount of electrical activity in lumbar extensor muscles during flexion compared with end of flexion range of movement).

† As reported by authors. Insufficient data for analysis.

‡ Single session intervention with pre and post analysis within session.

Table 2.5 Summary of results for studies that investigated intervention effects on lumbo-pelvic kinematic and postural patterns

Study and intervention type	No of subjects	Lumbo-pelvic kinematic and posture patterns (Standardised mean difference and 95% confidence intervals, values favour experimental group)							
		Movement pattern — Was there a statistically significant difference (p>0.05) in physical parameters *between* groups?						Health outcomes — Was there a statistically significant difference (p>0.05) in health outcomes between groups?	
		Baseline differences between groups?	Movement control	Gait	Standing posture	Respiration	Sitting posture	Pain	Activity
Da Fonesca 2009 *(Pilates vs No Rx group*	17	**No**	Not measured	**No**[*]	Not measured	Not measured	Not measured	**No** -0.61, (-1.59-0.37)	Not measured
Haugstad 2006 *(Mensendieck somatocognitive therapy vs gynaecological management)*	40	**No**	**No** -0.15 (-1.29,0.98)	**No** -0.47 (-1.12,0.17),	**No** -0.20 (-0.84,0.44)	**Yes** -0.99 (-1.67, -0.31)	**Yes** -0.69 (-1.35, -0.03)	**Yes**[§] -1.58 (-2.31,-0.85)	**Yes**[†]
Haugstad 2008 *(Mensendieck somatocognitive therapy vs gynaecological management) 12-month post intervention from Haugstad 2006*	38	**No**	**Yes** -1.07 (-1.75,-0.39)	**Yes** - 0.89 (-1.56,-0.23(	**No** **-0.56** **(-1.20,0.09)**	**Yes** -1.64 (-2.38,-0.91)	**Yes** -0.99 (-1.66,-0.31)	**Yes** -1.71 (-2.46,-0.97)	**Yes**[†]
Magnusson 2008 *(Postural biofeedback vs standardised rehabilitation)*	47	**No**[‖] Insufficient data	**Yes**[‡] Insufficient data	Not measured	Not measured	Not measured	Not measured	**Yes**[¶] -3.45 (-4.8 to -2.1)	**Yes**[¶] -0.97 (-0.43 to -0.12)

* No difference in gait-related parameters (vertical ground reaction forces at heel strike, mid stance, toes and rate of weight acceptance) between intervention and comparison groups except for a 3% increase in mid stance for the left leg only in the Pilates group.

† Measured as part of Mensendieck score, based on averaged scores for standing posture, movement, gait, sitting posture and respiration, p<0.000.

‡ As reported by author. Insufficient data provided for analysis.

§ Small baseline difference between groups p< 0.05.

‖ No baseline difference for pain or activity levels but insufficient data for physical parameters.

¶ Calculated on the lowest number of subjects.

2.2.5.   Discussion

Despite the popularity of concepts such as core stabilisation, movement normalisation and postural correction, we found only 12 trials that measured both physical change in the targeted patterns of muscle activation, lumbo-pelvic kinematics or postural patterns, and pain or activity limitation outcomes. The small number of studies available for review highlights the limited knowledge base about the ability of interventions to change movement patterns and the clinical relevance of these changes to patient-centred outcomes.

Do interventions consistently change muscle activity patterns?

Muscle activation patterns were included in this review as they represent a specific type of movement pattern and are reportedly linked to therapeutic change with appropriate interventions Effect sizes for muscle activity pattern changes were inconsistent, mostly non-significant and generally small to moderate in size. Inconsistency may be explained by a number of factors including measurement differences. For example, Ferreira et al (2010) demonstrated significant between group differences in post intervention TA thickness favouring motor control exercise over both general exercise and spinal manipulative therapy while Vasseljen et al (2010, 2012) , in a high quality study (QA 8/10) found no difference between motor control, sling or general exercise groups. The difference in results between these two trials may have occurred due to differences in trial method. Ferreira et al measured right sided, unilateral TA activity following isometric knee flexion/extension while Vasseljen et al measured bilaterally during an abdominal muscle drawing in manoeuvre. Recent evidence suggests that left and right TA can activate differentially depending on perturbation of the trunk (Morris, SL et al., 2012). Unilateral measurement may be insufficient to draw conclusions about TA activity and its role in movement control.

Trials that evaluated the effects of various interventions on patterns of FRR had mixed outcomes, with two trials showing significant improvements in the FRR favouring the intervention groups (Lalanne, K et al., 2009; Marshall, P et al., 2008) and two trials showing no difference (Mannion, AF et al., 2001b; Ritvanen, T et al., 2007). Methodological differences between trials may also account for these variations in results. Marshall et al (2008) demonstrated a positive change to the FRR for a group of people with chronic LBP who performed high load, Swiss ball exercise (compared with general

exercise) over a three-month period, while Lalanne et al (2009) used a within-session design comparing manipulative treatment with sham treatment, that demonstrated an immediate positive change to the FRR. The very different designs and interventions confound interpretation and comparison of results. Measurement and classification differences in the calculation of the FRR further constrain comparison of these four studies. Mannion et al (2001a; 1999a) used visual assessment to grade post-intervention changes to the FRR as 'improved, same, or worse' while the other three trials computed a ratio of electrical activity in the movement period to electrical activity in the fully flexed period but used different formulae to compute this ratio. It is possible that people with LBP may have significant variation of flexion relaxation responses. It is also plausible that not all interventions will equally affect the FRR. Dankaerts et al (2006b, 2006c) demonstrated that different patterns of muscle activation and FRR are seen in people with chronic LBP during sitting. When comparing a group of unimpaired people with people with chronic LBP, no differences were identified until people with LBP were sub-classified into groups dependent on whether flexion or extension activity provoked pain. The group classified as having pain provoked by extension showed higher lumbar extensor muscle contraction activity, while the group with pain provoked by flexion showed lower levels of muscle activity in sitting when compared with the no-pain control group. If such patterns of muscle activation, posture and movement do exist and are clinically meaningful, this could affect the results of clinical trials. In theory, a trial with a greater proportion of participants with a particular pattern of chronic LBP may have different outcomes compared to trials of participants with different patterns of muscle activation.

The relationship of change to muscle activation patterns and changes to pain and activity limitation

The available evidence suggests little consistent relationship exists between changes to pain and/or activity level and the direction of changes to muscle activity. Changes to muscle activation patterns have been reported without corresponding change to pain or activity, while the opposite has also been reported. One could reasonably expect that if a muscle activation deficit was consistently contributing to pain or activity restriction in the broad population of people with LBP, improvements in pain and activity level would occur in conjunction with improvement in that muscle deficit. Five trials investigated changes in TA activity, with only one reporting an association between changes in TA function and associated changes in pain or activity limitation. Two trials, one involving people with acute LBP (Hides,

54

J et al., 1996) and the other with chronic LBP (Akbari, A et al., 2008b), investigated Lumbar Multifidus (LM) function following motor control exercise interventions. The Hides trial (Hides, J et al., 1996) of people with acute LBP suggests that improvement in LM size is not directly associated with improvement in pain or activity levels. The Akbari trial (Akbari, A et al., 2008b) of people with chronic LBP that compared motor control with general exercise, found no significant post-intervention differences between groups for TA or LM size, but did find a significant improvement in pain and activity favouring the motor control group. Both the Hides and Akbari trials used ultrasound measurement of LM, which has been shown to be sensitive to changes in lumbar and abdominal muscle (Koppenhaver, SL et al., 2009). These findings provide preliminary evidence that changes in pain and/or activity can occur without observable change to TA or LM size and *vice versa*. O'Sullivan et al (1998; 1997) found a significant difference in a pattern of muscle activation (ratio of deep to superficial abdominal muscle activity), and also in both pain and activity levels, favouring motor control exercise. However, the O'Sullivan et al study differs from other studies by investigating a subgroup of chronic LBP subjects (spondylolisthesis with specific symptom pattern), while the other studies in this review included people with non-specific chronic LBP. It also differs from the other included studies with respect to the large differences observed between intervention (motor control) and control (medical management) outcomes. The improvement seen in muscle activation patterns and the related improvements in pain and activity warrant replication in another study if clinicians are to have confidence that similar outcomes would occur in the general LBP population. Recent reviews of motor control exercise for general chronic LBP populations have not concluded similar effects for pain or activity (Ferreira, ML et al., 2007; Macedo, LG et al., 2009; May, S et al., 2008) and no other trials could be found that measured the ratio of deep to superficial muscle activity.

No picture emerged of a relationship between change in FRR and change in pain and activity. Marshall et al (2008) found statistically significant improvement in activity limitation favouring the experimental group. However, neither of the two trials (Lalanne, K et al., 2009; Marshall, P et al., 2008) that found improvement in FRR favouring the intervention group, were associated with any difference between groups for pain outcomes. Geisser et al (2005) in a systematic review found 11 studies comparing EMG of dynamic lumbar extensor muscle activity of people with chronic LBP with normal subjects, four of which specifically examined differences in the FRR. Based on meta-analytic pooling data from four comparable studies, they concluded that the evidence supports the FRR being a useful, measurable

movement characteristic that differentiates people with LBP from people without LBP (SMD = -1.71, 95%CI -2.25 to -1.36). A recent pilot study of chronic LBP (Neblett, R et al., 2010) showed that EMG biofeedback plus functional restoration was better than functional restoration alone in improving FRR. However, the relationship between change to the FRR and changes to pain or activity limitation remains poorly explored. Increased standardisation of FRR measurement combined with a better understanding of typical variability in FRR in people with chronic LBP will be required before the implications of measuring and modifying the FRR become clear.

Lumbo-pelvic kinematic and postural patterns

Three trials examined lumbo-pelvic kinematic and postural patterns, with only one focused on posture. The concept of changing movement or postural patterns is fundamental to many popular movement-based interventions but is rarely measured in trials of the effects of interventions. Magnusson (2008) reported changes to lumbo-pelvic circumduction area favouring the postural biofeedback intervention group with associated improvements in pain and activity also favouring the intervention group. The effect sizes favouring the postural biofeedback intervention group were unusually large, and a replication study is therefore warranted. Haugstad et al (2006, 2008) found large and statistically significant effects in respiration and posture in favour of the intervention group using Mensendieck therapy for women with non-specific pelvic pain, as well as significant improvements in pain and activity limitation. At 12-month follow-up, the intervention group showed further improvement in movement control, gait, respiration and posture, and reduction in pain relative to the control group. In contrast, a trial by Soukup and Glomsrod (1999) comparing Mensendieck therapy to a no treatment control group for people with chronic LBP found that although 12-month recurrence rates were significantly lower for the intervention group, there were no post-intervention differences between groups for pain or activity limitation. Despite a common assumption that posture is related to LBP, studies of interventions that include measurement of changes to posture are scarce, and a relationship between postural modification and improvements to pain or activity limitation has not been established.

Measurement methods and reliability

It was beyond the scope of this review to assess the reliability of instruments used to measure movement patterns. However, clinicians and researchers need to remain attentive to how movement patterns can be reliably measured and the minimal amount of change required for clinical relevance.

Study limitations

The strengths of this systematic review are the comprehensive search strategy of a diverse selection of electronic databases, screening and data extraction by two independent reviewers. Furthermore, included studies needed to quantify a change in the targeted movement pattern so as to link that physical outcome with subsequent changes in patient-centred outcomes. The review also has limitations. Due to an absence of translation resources, only articles published in English were included and this may introduce a language, cultural and/or publication bias. The classification categories of movement patterns were necessarily arbitrary but were designed to include the most common characteristics observed in practice.

2.2.6.   Conclusions

This review establishes that despite the popularity of movement-related interventions, there are few clinical trials that quantify the effect of interventions for people with LBP on the outcomes of change in muscle activity, lumbo-pelvic kinematic or postural patterns. The available evidence on muscle activity pattern changes following therapeutic interventions indicates little difference in outcomes between a general exercise program and specific interventions that aim to change the activity of trunk muscles such as Transversus Abdominus and Lumbar Multifidus. That same evidence suggests that improved pain or activity limitation are consistently unrelated to changes in the activity of specific muscles. There is conflicting evidence of the effectiveness of interventions that measure changes to the flexion relaxation response, possibly due to differing trial designs and participant differences. The relationship between intervention-related change to the flexion relaxation response and changes to pain or activity limitation are also unclear. Trials of interventions that aim to change lumbo-pelvic kinematic and postural patterns are few in number, and too varied in design, to draw firm conclusions.

Overall, our ability to change movement patterns with specific interventions is not well supported by the research currently available. There is little evidence that pain and activity limitation change in concert with desirable changes to movement patterns. More research with better designs is required to advance our understanding of movement-modification through exercise.

Abbreviations:

Low Back Pain = LBP
Transversus Abdominus =TA
Lumbar Multifidus = LM
Internal Oblique = IO
External Oblique =EO
Standardised Mean Difference =SMD
Flexion Relaxation Response = FRR

Competing interests

No funding was received for this systematic review. No benefits in any form have been, or will be, received from a commercial party related directly or indirectly to the subject of this paper. This paper does not contain information about medical devices or drugs. The authors hold no stocks or shares in any company that might be directly or indirectly affected by this review. No patents have been applied for or received due to the content of this review. There are no non-financial competing interests associated with this review.

Authors Contributions

RL and PK contributed to data collection. RL and PK performed data inclusion and extraction with JK providing arbitration when required. All authors were involved in the design of the review, analysis and interpretation of data, drafting & revision of the manuscript, and gave approval of the final manuscript.

2.2.7. Bibliography for Laird et al (2012)

Akbari A, Khorashadizadeh S, Abdi G: The effect of motor control exercise versus general exercise on lumbar local stabilizing muscles thickness: randomized controlled trial of patients with chronic low back pain. *J Back Musculoskel Rehabil* 2008, 21(2):105-112.

Battié MC, Videman T, Kaprio J, Gibbons LE, Gill K, Manninen H, Saarela J, Peltonen L: The Twin Spine Study: Contributions to a changing view of disc degeneration. *Spine J* 2009, 9(1):47-59.

Bryan M, Hawson S: The Benefits of Pilates Exercise in Orthopaedic Rehabilitation. *Techniques in Orthopaedics March* 2003, 18(1):126-129.

da Fonseca JL, Magini M, de Freitas TH: Laboratory gait analysis in patients with low back pain before and after a pilates intervention. *J Sport Rehabil* 2009, 18(2):269-282.

Dankaerts W, O'Sullivan P, Burnett A, Straker L, Dankaerts W, O'Sullivan P, Burnett A, Straker L: Differences in sitting postures are associated with nonspecific chronic low back pain disorders when patients are subclassified. *Spine* 2006, 31(6):698-704.

Dankaerts W, O'Sullivan P, Burnett A, Straker L, Dankaerts W, O'Sullivan P, Burnett A, Straker L: Altered patterns of superficial trunk muscle activation during sitting in nonspecific chronic low back pain patients: importance of subclassification. *Spine* 2006, 31(17):2017-2023.

de Fonseca JL, Magini M, de Freitas TH: Laboratory gait analysis in patients with low back pain before and after a Pilates intervention. *J Sport Rehabil* 2009, 18(2):269-282.

de Morton N: The PEDro scale is a valid measure of the methodological quality of clinical trials: a demographic study. *J Physiother* 2009, 55(2):192-133.

Descarreaux M, Blouin J-S, Teasdale N: Repositioning accuracy and movement parameters in low back pain subjects and healthy control subjects. *Eur Spine J* 2005, 14(2):185-191.

Dunk NM, Callaghan JP: Lumbar spine movement patterns during prolonged sitting differentiate low back pain developers from matched asymptomatic controls. *Work* 2010, 35(1):3-14.

Ernst E, Canter PH: The Alexander technique: a systematic review of controlled clinical trials. *Forsch Komplementarmed Klass Naturheilkd* 2003, 10(6):325-329.

Esola MA, McClure PW, Fitzgerald GK, Siegler S: Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain. *Spine* 1996, 21(1):71-78.

Ferreira ML, Ferreira PH, Latimer J, Herbert RD, Hodges PW, Jennings MD, Maher CG, Refshauge KM: Comparison of general exercise, motor control exercise and spinal manipulative therapy for chronic low back pain: A randomized trial. *Pain* 2007, 131(1-2):31-37.

Ferreira P, Ferreira M, Maher C, Herbert R, Refshauge K: Specific stabilisation exercise for spinal and pelvic pain: A systematic review. *J Physiother* 2006, 52:79-88.

Ferreira P, Ferreira M, Maher C, Refshauge K, Herbert R, Hodges P: Changes in recruitment of transversus abdominis correlate with disability in people with chronic low back pain. *Br J Sports Med* 2010, 44:1166-1172.

Ferreira PH, Ferreira ML, Hodges PW: Changes in recruitment of the abdominal muscles in people with low back pain ultrasound measurement of muscle activity. *Spine* 2004, 29(2):2560–2566.

Freeman MD, Woodham MA, Woodham AW: The role of the lumbar multifidus in chronic low back pain: a review. *Pm & R* 2010, 2(2):142-146; quiz 141 p following 167.

Geisser ME, Ranavaya M, Haig AJ, Roth RS, Zucker R, Ambroz C, Caruso M: A meta-analytic review of surface electromyography among persons with low back pain and normal, healthy controls. *J Pain* 2005, 6(11):711-726.

Gregory DE, Callaghan JP, Gregory DE, Callaghan JP: Prolonged standing as a precursor for the development of low back discomfort: an investigation of possible mechanisms. *Gait Posture* 2008, 28(1):86-92.

Hauggaard A, Persson AL: Specific spinal stabilisation exercises in patients with low back pain -- a systematic review. *Phys Ther Rev* 2007, 12(3):233-248.

Haugstad GK, Haugstad TS, Kirste UM, Leganger S, Klemmetsen I, Malt UF: Mensendieck somatocognitive therapy as treatment approach to chronic pelvic pain: results of a randomized controlled intervention study. *Am J Obstet Gynecol* 2006, 194(5):1303-1310.

Haugstad GK, Haugstad TS, Kirste UM, Leganger S, Wojniusz S, Klemmetsen I, Malt UF: Continuing improvement of chronic pelvic pain in women after short-term Mensendieck somatocognitive therapy: results of a 1-year follow-up study. *Am J Obstet Gynecol* 2008, 199(6):615.e611-618.

Hides J, Gilmore C, Stanton W, Bohlscheid E: Multifidus size and symmetry among chronic LBP and healthy asymptomatic subjects. *Man Ther* 2008, 13(1):43-49.

Hides JA, Jull GA, Richardson CA: Long-term effects of specific stabilizing exercises for first-episode low back pain. *Spine* 2001, 26(11):E243-248.

Hides JA, Richardson CA, Jull GA: Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain. *Spine* 1996, 21(23):2763-2769.

Hodges P, Richardson C: Inefficient muscular stabilization of the lumbar spine associated with low back pain: a motor control evaluation of transversus abdominus. *Spine* 1996, 21(22):2640-2650.

Hodges P, van den Hoorn W, Dawson A, Cholewicki J: Changes in the mechanical properties of the trunk in low back pain may be associated with recurrence. *J Biomech* 2009, 42(1):61-66.

Kent P, Keating JL: Classification in non-specific low back pain - what methods do primary care clinicians currently use? *Spine* 2005, 30:1434-1440.

Koes B, van Tulder, M., and Thomas, S: Diagnosis and treatment of low back pain. *Br Med J* 2006, 332:1430-1434.

Koppenhaver SL, Hebert JJ, Parent EC, Fritz JM: Rehabilitative ultrasound imaging is a valid measure of trunk muscle size and activation during most isometric sub-maximal contractions: a systematic review. *J Physiother* 2009, 55(3):153-169.

Lalanne K, Lafond D, Descarreaux M: Modulation of the flexion-relaxation response by spinal manipulative therapy: a control group study. *J Manipulative Physiol Ther* 2009, 32(3):203-209.

Lee J, Hoshino Y, Nakamura K, Ooi Y: Trunk muscle imbalance as a risk factor of the incidence of low back pain: a 5-year propsective [sic] study. *J Neuomusculoskeletal Syst* 1999, 7(3):97-101.

Lim ECW, Poh RLC, Low AY, Wong WP: Effects of Pilates-Based Exercises on Pain and Disability in Individuals With Persistent Nonspecific Low Back Pain: A Systematic Review With Meta-analysis. *J Orthop Sports Phys Ther* 2011, 41(2):70-80.

Little P, Lewith G, Webley F, Evans M, Beattie A, Middleton K, Barnett J, Ballard K, Oxford F, Smith P *et al*: Randomised controlled trial of Alexander technique lessons, exercise, and massage (ATEAM) for chronic and recurrent back pain.[see comment]. *BMJ* 2008, 337:a884.

Macedo LG, Maher CG, Latimer J, McAuley JH: Motor Control Exercise for Persistent, Nonspecific Low Back Pain: A Systematic Review. *Phys Ther* 2009, 89(1):9-25.

Magnusson ML, Chow DH, Diamandopoulos Z, Pope MH: Motor control learning in chronic low back pain. *Spine* 2008, 33(16):E532-538.

Maher CG, Sherrington C, Herbert RD, Moseley AM, Elkins A: Reliability of the PEDro scale for rating quality of randomized controlled trials. *Phys Ther* 2003, 83:713-721.

Mannion AF, Junge A, Taimela S, Muntener M, Lorenzo K, Dvorak J: Active therapy for chronic low back pain: part 3. Factors influencing self-rated disability and its change following therapy. *Spine* 2001, 26(8):920-929.

Mannion AF, Muntener M, Taimela S, Dvorak J: 1999 Volvo Award Winner in Clinical Studies: a randomized clinical trial of three active therapies for chronic low back pain. *Spine* 1999, 24(23):2435-2448.

Mannion AF, Taimela S, Muntener M, Dvorak J: Active therapy for chronic low back pain part 1. Effects on back muscle activation, fatigability, and strength. *Spine* 2001, 26(8):897-908.

Marshall P, Murphy B: Muscle activation changes after exercise rehabilitation for chronic low back pain. *Arch Phys Med Rehabil* 2008, 89(7):1305-1313.

May S, Johnson R: Stabilisation exercises for low back pain: a systematic review. *Physiotherapy* 2008, 94(3):179-189.

McClure PW, Esola M, Schreier R, Siegler S: Kinematic analysis of lumbar and hip motion while rising from a forward, flexed position in patients with and without a history of low back pain. *Spine* 1997, 22(5):552-558.

McKenzie R, May S: Lumbar Spine, Mechanical Diagnosis and Therapy, 2nd edn. Waikanae, New Zealand: Spinal Publications Ltd; 2003.

Morris SL, Lay B, Allison GT: Corset hypothesis rebutted — Transversus abdominis does not co-contract in unison prior to rapid arm movements. *Clinical Biomechanics* 2012 27:249-254.

Neblett R, Mayer TG, Brede E, Gatchel RJ: Correcting abnormal flexion-relaxation in chronic lumbar pain: responsiveness to a new biofeedback training protocol. *Clin J Pain* 2010, 26(5):403-409.

Neblett R, Mayer TG, Gatchel RJ, Keeley J, Proctor T, Anagnostis C: Quantifying the lumbar flexion-relaxation phenomenon: theory, normative data, and clinical applications. *Spine* 2003, 28(13):1435-1446.

O'Sullivan P, Twomey L, Allison G: Altered abdominal muscle recruitment in patients with chronic back pain following a specific exercise intervention. *J Orthop Sports Phys Ther* 1998, 27(2):114-124.

O'Sullivan P, Twomey LT, Allison GT: Evaluation of specific stabilizing exercise in the treatment of chronic low back pain with radiologic diagnosis of spondylolysis or spondylolisthesis. *Spine* 1997, 22(24):2959-2967.

Rackwitz B, DeBie R, Ewert T, Stucki G: Segmental stabilizing exercises and low back pain. What is the evidence? A systematic review of randomized controlled trials. *Clin Rehabil* 2006, 20:553-567.

Review Manager (RevMan) In., 5.0 edn. Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration.; 2008.

Richardson C, Jull G, Hodges P, Hides J: Therapeutic exercise for spinal segmental stabilization in low back pain : scientific basis and clinical approach. Edinburgh: Churchill Livingstone; 1999.

Ritvanen T, Zaproudina N, Nissen M, Leinonen V, Hänninen O: Dynamic Surface Electromyographic Responses in Chronic Low Back Pain Treated by Traditional Bone Setting and Conventional Physical Therapy. *J Manipulative Physiol Ther* 2007, 30(1):31-37.

Scannell J, McGill S: Lumbar posture-should it, and can it, be modified? A study of passive tissue stiffness and lumbar position during activities of daily living. *Phys Ther* 2003, 83(10):907-917.

Shum GL, Crosbie J, Lee RYW: Three-Dimensional Kinetics of the Lumbar Spine and Hips in Low Back Pain Patients During Sit-to-Stand and Stand-to-Sit. *Spine* 2007, 32(7):E211-E219.

Silfies SP, Bhattacharya A, Biely S, Smith SS, Giszter S: Trunk control during standing reach: A dynamical system analysis of movement strategies in patients with mechanical low back pain. *Gait Posture* 2009, 29(3):370-376.

Silfies SP, Mehta R, Smith SS, Karduna AR: Differences in Feedforward Trunk Muscle Activity in Subgroups of Patients With Mechanical Low Back Pain. *Arch Phys Med Rehabil* 2009, 90(7):1159-1169.

Slade SC, Keating JL: Trunk-strengthening exercises for chronic low back pain: a systematic review. *J Manipulative Physiol Ther* 2006, 29(2):163-173.

Slade SC, Keating JL: Unloaded movement facilitation exercise compared to no exercise or alternative therapy on outcomes for people with nonspecific chronic low back pain: a systematic review. *J Manipulative Physiol Ther* 2007, 30(4):301-311.

Smith A, O'Sullivan P, Straker L: Classification of sagittal thoraco-lumbo-pelvic alignment of the adolescent spine in standing and its relationship to low back pain. *Spine* 2008, 33(19):2101-2107.

Soukup MG, Glomsrod B, Lonn JH, Bo K, Larsen S: The effect of a Mensendieck exercise program as secondary prophylaxis for recurrent low back pain. A randomized, controlled trial with 12-month follow-up. *Spine* 1999, 24(15):1585-1591; discussion 1592.

Teyhen DS, Flynn TW, Childs JD, Abraham LD: Arthrokinematics in a subgroup of patients likely to benefit from a lumbar stabilization exercise program. *Phys Ther* 2007, 87(3):313-325.

Unsgaard-Tondel M, Fladmark AM, Salveson O, Vasseljen O: Motor control exercises, sling exercises and general exercises for patients with CLBP: a RCT with 1 year follow-up. *Physical Therapy* 2010, 90(10):1-14.

Van Daele U, Hagman F, Truijen S, Vorlat P, Van Gheluwe B, PhD, Vaes P: Decrease in postural sway and trunk stiffness during cognitive dual-task in nonspecific chronic low back pain patients, performance compared to healthy control subjects. *Spine* 2010, 35(5):583-589.

Van Dillen LR, Sahrmann SA, Norton BJ, Caldwell CA, McDonnell MK, Bloom N: The effect of modifying patient-preferred spinal movement and alignment during symptom testing in patients with low back pain: a preliminary report. *Arch Phys Med Rehabil* 2003, 84(3):313-322.

van Middelkoop M, Rubinstein SM, Verhagen AP, Ostelo RW, Koes BW, van Tulder MW: Exercise therapy for chronic nonspecific low-back pain. *Best Pract Clin Rheumatol* 2010, 24(2):193-204.

Vasseljen O, Fladmark AM: Abdominal muscle contraction thickness and function after specific and general exercises: A randomized controlled trial in chronic low back pain patients. *Man Ther* 2010, 15(5):482-489.

Vasseljen O, Unsgaard-Tondel M, Westad C, Mork P: Effect of Core Stability Exercises on Feedforward Activation of Deep Abdominal Muscles in Chronic Low Back Pain: A Randomized Controlled Trial. *Spine* 2012.

Verhagen AP, de Vet HCW, de Bie RA, Kessels AGH, Boers M, Bouter LM, Knipschild PG: The Delphi List: A Criteria List for Quality Assessment of Randomized Clinical Trials for Conducting Systematic Reviews Developed by Delphi Consensus. *J Clin Epidemiol* 1998, 51(12):1235-1241.

Waddell G: Low Back Pain: A Twentieth Century Health Care Enigma. *Spine* 1996, 21(24):2820-2825.

Wallwork TL, Stanton WR, Freke M, Hides JA: The effect of chronic low back pain on size and contraction of the lumbar multifidus muscle. *Man Ther* 2009, 14(5):496-500.

Watson P, Booker C, Main C, Chen A: Surface electromyography in the identification of chronic low back pain patients: the development of the flexion relaxation ratio. *Clinical Biomechanics* 1997, 12:165-171.

Weiner BK: The biopsychosocial model and spine care. *Spine* 2008, 33(2):219–223.

Williams MM, Hawley JA, McKenzie RA, van Wijmen PM: A comparison of the effects of two sitting postures on back and referred pain. *Spine* 1991, 16(10):1185-1191.

2.3. Summary of findings and a comparison with subsequent research

The review found clinical trials that investigated three types of movement patterns: abdominal muscle activation patterns, activation patterns of lumbar extensor muscles during flexion (also known as the flexion relaxation response or FRR) and general postural/movement patterns. It led to the conclusion that the effect of movement-based interventions on changing specific movement parameters was mostly small to moderate, and inconsistent across studies. Similarly, where changes to a movement parameter were reported, there were inconsistent relationships observed in improvements in pain or activity limitation. If an important relationship exists between changes in a movement-related pattern and changes in pain and activity limitation, one would at least expect to see a consistent *direction* of relationship i.e. both parameter and pain/activity limitation show some improvement, even if the strength of the relationship changed between different samples and trial methods. This review concluded that the nature of any relationships between changes in muscle activation, movement or posture patterns and changes in symptoms is not apparent from the included studies.

2.3.1. The relationship of changing muscle activation patterns with changes to pain and/or activity limitation: other research

Following the publication of Laird et al. (2012), several systematic reviews have been published on trials of interventions addressing altered muscle activation patterns using stabilisation-type exercises (Bystrom, MG et al., 2013; Saragiotto, B et al., 2016; Smith, BE et al., 2014; Wong, A et al., 2013). Bystrom et al. (2013) reviewed 16 randomised controlled trials (RCTs) and concluded that motor control exercises were superior in reducing LBP and activity limitation to other forms of active treatment. However, the superior outcomes reported by Bystrom et al. were much smaller (on average) than the amount of change required to be clinically meaningful (Dworkin, RH et al., 2008). Smith et al. (2014) reviewed 29 studies of stabilisation exercises with broader inclusion criteria and concluded that "*stabilisation exercises are not more effective than any other form of active exercise in the long term*". Saragiotto et al. (2016, p. 416) reviewed 32 trials comparing motor control exercises with no treatment or other active treatments and reached similar conclusions to Smith et al., that motor control exercises were superior to no treatment but resulted in similar effects compared with other active interventions on pain and activity limitation. None of these three reviews reported on changes to the targeted muscle

activation patterns following interventions. Only one review considered changes to the targeted muscle activation patterns associated with stabilisation exercise. Wong et al. (2014, pp. e13-14) systematically reviewed 15 studies that specifically measured muscle activation parameters of transversus abdominis and lumbar multifidus and concluded there was "*strong evidence that temporal alterations in transversus abdominis thickness change during contraction…, or feedforward activation of transversus abdominis…, were unrelated to temporal changes in low back pain or LBP-related activity limitation*". The review also concluded that there was conflicting evidence about a relationship between changes in lumbar multifidus size and changes in pain and activity limitation. In summary, although there is some evidence that stabilisation interventions might change movement parameters, there is little evidence of any relationship between changes in muscle activation patterns arising from stabilisation-type exercises and changes in pain or activity limitation.

2.3.2. The relationship of changes in posture and other movement patterns with changes in pain and/or activity limitation: other research

Only a small number of trials measured changes in movement patterns or posture, despite the longstanding belief that posture is important (Jain, S et al., 2005; Woodman, JP et al., 2012). There have been few attempts to measure posture modification for persistent LBP. Brody et al. (2017) used a case-series design to test a particular postural-based intervention, using visual measurements of posture. They classified each person into one of 16 possible subgroups then provided a specific intervention matched to each defined subgroup classification. They found a significant change in the number of 'postural imbalances' with accompanying improvements in pain and activity limitation, however, there was no report of any quantified measurements of posture. A large randomised trial compared the Alexander technique, massage and advice for 579 people with chronic LBP and reported improved activity limitation following 24 Alexander technique lessons compared with normal care, but did not measure any physical outcomes (Little, P et al., 2008b). This lack of measurement raises questions about why movement patterns are not routinely measured and reported despite their clinical popularity. The most likely answer lies in the difficulty in measuring movement and postural parameters in a clinical setting with tools that are sufficiently accurate and reliable for typical clinical use and that are also not time-intensive. Laboratory-based measurement tools are available, but these tools are complex and expensive, take time to apply and are not typically available to clinicians. Nevertheless, if

the targeted parameter is not measured at baseline and at subsequent points through or following intervention, then no evidence can be gathered on how changes in targeted movement parameters relate to changes in pain and activity limitation.

2.3.3. Changes in movement patterns are inconsistent with little association with changes in pain and activity limitation: Research limitations

The association between changes in lumbo-movement patterns and changes in pain and activity limitation reported in Laird et al. (2012) and other reviews, is unclear due to inconsistent results between studies. There are a number of possible explanations for these inconsistent results.

Participants often differ between studies on the basis of pain intensity and activity limitation. For example, at baseline, participants in the trial by Akbari et al. (2008a) had mean pain scores (0-100% scale) of 72% and 80% for the intervention and control respectively, indicating higher pain intensity compared with much lower baseline pain intensity scores of 26% and 23% for subjects in the study by Lalanne et al. (2009). It would be reasonable to consider that people in a lot of pain may have a different capacity to respond to an intervention, at least in terms of pain intensity, than those who already have low baseline pain and activity limitation levels. If people with higher pain had greater prevalence of non-normal movement, then participants with high pain may be better targets for investigation into the relationship between changes in movements and changes in pain.

Sampling issues may conceal associations between movement and pain, if any association does indeed exist. If specific movement deficits are only present in a small percentage of people with LBP, then the relatively small representation of such subjects in a study might cause type 2 errors. For instance, if only 25% of a particular sample of people with persistent LBP have a specific aberrant muscle activation pattern e.g. weak or delayed transversus abdominis activity, then any interventions aimed at restoring or improving that particular muscle activation pattern are less likely to have any effect on pain/activity limitation in the 75% of people who did not have the altered parameter to start with. A similar logic can be applied to a loss of ROM. If loss of ROM only occurs in a subgroup of people with LBP, then strategies to increase ROM may not lead to significant changes in ROM or an observable relationship between such changes and symptoms averaged across outcomes for group participants.

If one is to investigate the potential benefit of an intervention designed to improve a movement-related parameter, then it seems logical that those people with a deficit of that movement parameter would be more likely to respond than those who do not have a deficit of that particular parameter. Ferreira et al. (2010) compared transversus abdominis activity (a ratio of muscle thickness during contraction to thickness at rest) in three small groups who received 12 treatment sessions of motor control exercise (n=11), general exercise (n=10), and spinal manipulative therapy (n=13). They found a non-significant (p=.07) increase in transversus abdominis thickness for the motor control exercise group, and no differences between groups for mean pain or activity limitation scores. However, when the data for all 34 subjects from the three groups were pooled, (to test the correlation between changes in transversus abdominis activity and changes in pain/activity limitation) there was a significant moderate correlation (r= -0.35 95%CI 0.02 -0.62) between improvements to transversus abdominis function and disability (activity limitation). Wong et al. (2013) systematically reviewed baseline characteristics of transversus abdominis and lumbar multifidus to determine whether these were predictors of clinical outcomes in people with non-specific LBP. They described limited evidence from five cohort studies suggesting that poor baseline transversus abdominis thickness ratio was a predictor (potential treatment effect modifier) of better outcomes with motor control exercise (compared with general exercise). Future research into interventions that aim to improve movement-related patterns should consider only including participants with a target deficit.

2.4. Is it important to measure movement in people with LBP?

Laird et al. (2012) chose to examine the effect of randomised trials on interventions that were intended to change patterns of movement. This focus on movement *patterns* was in response to two types of interventions that were popular prior to 2012: (i) interventions that aimed to change muscle activation patterns based on a concept of 'core stability' and (ii) interventions that aimed to change movement patterns based on subgrouping movement-related classification systems. Laird et al. (2012) limited their search to RCTs that measured patterns of movement, including muscle activation, movement and postural patterns, but did not include general or singular lumbo-pelvic kinematic (lumbo-pelvic kinematic) parameters such as ROM, velocity/acceleration, timing and regional movement contributions (i.e. lumbo-pelvic rhythm), sitting or standing pelvic tilt angles or postural features such as lumbar lordosis.

Steiger et al. (2011) published a systematic review and meta-analysis on the effects of exercise on ROM, strength and endurance in people with chronic LBP, aspects of movement that were not assessed in Laird et al. (2012). They searched for trials published prior to 2010 and found 16 trials, 11 of which measured physiological ROM in some way. Eight of these trials ((Ben Salah Frih, Z et al., 2009; Demoulin, C et al., 2006; Khalil T et al., 1992; Kofotolis, N et al., 2006; Mannion, AF et al., 1999b; Mellin, G et al., 1993; Rittweger, J et al., 2002; Taimela, S et al., 1996) measured lumbar ROM only, two measured fingertip-to-floor (Elnaggar, IM, 1991; Roche, G et al., 2007) and one used a combined ROM score for all directions of movement (Johannsen, F et al., 1995). The review concluded that there was little association between changes to ROM and improvements in pain and activity limitation, but there are constraints on interpreting the findings of the review by Steiger et al. The inconsistency of results between studies for changes in ROM, the fact that eight out of 11 studies only measured lumbar ROM, and the lack of knowledge from the studies included in the review about how many people had atypical ROM at baseline, makes it difficult to know if change in ROM (or other lumbo-pelvic kinematic parameters) is important for some individuals and how improvements in movement parameters are associated with improvements in pain or activity limitation.

In summary, there is little evidence of the effectiveness of interventions that attempt to change movement patterns, or ROM-related lumbo-pelvic kinematic parameters, suggesting that interventions are not very effective at changing the targeted movement parameters or that our measurements of lumbo-pelvic kinematic parameters lack precision. There are those who question if measuring aspects of movement should have the focus they have had (Pengel, LH et al., 2004; Sullivan, MS et al., 2000). Pengel et al. (2004) compared the responsiveness of pain, activity limitation and ROM measurements at baseline and 6 weeks after an intervention for 156 people with subacute LBP. They found that the effect on activity limitation (effect size = 1.6 for patient-specific functional scale and 0.8 for a Roland Morris Disability Questionnaire) and pain (effect size 1.3 for a numerical rating scale) were much larger than the responsiveness of ROM measurements, including straight leg raise (effect sizes ranged from 0.1 to 0.6). They concluded that "*Physical impairments are routinely measured in clinical practice and clinical research, but the lower responsiveness indicates that this approach is not optimal. Our findings suggest that more emphasis should be placed on change in pain and disability scores than on change in physical impairments.*" (Pengel, LH et al., 2004, p. 879).

There are divergent views about the utility of measuring lumbo-pelvic movement and questions about the relevance of measuring lumbo-pelvic movement in people with LBP remain unanswered. If lumbo-pelvic movement is relevant to people with persistent LBP, then movement-related differences compared with those without LBP should be evident.

3. Chapter 3 – Comparing lumbo-pelvic movement in people with and without persistent LBP

3.1. Introduction

Observation of movement is a fundamental assessment approach used by clinicians to examine how movement and pain are related in people with LBP. To identify potentially aberrant lumbo-pelvic kinematic parameters, it is first necessary to be able to distinguish between movements that are normal and movements that are not normal. If lumbo-pelvic kinematic parameters are linked to pain or activity limitation, these parameters should be different when compared to people without LBP. Clinical assessment of lumbo-pelvic kinematic parameters is generally limited to non-invasive measurements, as invasive and imaging options are expensive, have potential health risks and are relatively inaccessible for most clinicians and patients.

The first systematic review of this thesis examined if changes in movement *patterns* correlated with changes in pain or activity limitation. The next stage of this thesis was to review what is known about *specific lumbo-pelvic kinematic parameters* for people with and without persistent LBP measured using non-invasive measurement techniques.

Such a review would guide this research with respect to which parameters have been studied, how these parameters were measured and whether there were observed differences between groups. If there is an association between movement and pain, then movement-related differences should be seen between people with and without LBP. The following systematic review "Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis" was published in BMC Musculoskeletal Disorders in 2014. It has been viewed 8487 times and cited 51 times. The following section (3.2) is an identical Word document version of Laird et al. (2014), reproduced within the thesis to enable higher-quality text, suitable for printing if required. The published PDF version (see Figure 3.1) can be seen in Appendix D and an electronic copy of the PDF is available via open access at: https://bmcmusculoskeletdisord.biomedcentral.com/articles/10.1186/1471-2474-15-229

3.2. Comparing lumbo-pelvic kinematics in people with and without persistent LBP: a systematic review and meta-analysis

Robert A Laird[1]

Email:

Jayce Gilbert[2]

Email:

Peter Kent[3, 4]

Email:

Jennifer L Keating[1]

Email:

[1] Department of Physiotherapy, Monash University, PO Box 527, Frankston, Victoria 3199, Australia

[2] Peak MSK Physiotherapy, Suite 4 / 544 Hampton St, Victoria 3188, Australia

[3] Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense 5230, Denmark

[4] Research Department, Spine Centre of Southern Denmark, Lillebaelt Hospital, Institute of Regional Health Services Research, University of Southern Denmark, Middelfart 5500, Denmark

[*] Corresponding author. Robert Laird, 7 Kerry Rd, Warranwood, Melbourne, Victoria 3134, Australia

RESEARCH ARTICLE   **Open Access**

Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis

Robert A Laird[1,5*], Jayce Gilbert[2], Peter Kent[3,4] and Jennifer L Keating[1]

Figure 3.1 The PDF version of this paper is available in Appendix D

3.2.1.   Abstract

Background

Clinicians commonly examine posture and movement in people with the belief that correcting dysfunctional movement may reduce pain. If dysfunctional movement is to be accurately identified, clinicians should know what constitutes normal movement and how this differs in people with low back pain (LBP). This systematic review examined studies that compared biomechanical aspects of lumbo-pelvic movement in people with and without LBP.

Methods

MEDLINE, Cochrane Central, EMBASE, AMI, CINAHL, Scopus, AMED, ISI Web of Science were searched from inception until January 2014 for relevant studies. Studies had to compare adults with and without LBP using skin surface measurement techniques to measure lumbo-pelvic posture or movement. Two reviewers independently applied inclusion and exclusion criteria, and identified and extracted data. Standardised mean differences and 95% confidence intervals were estimated for group differences between people with and without LBP, and where possible, meta-analyses were performed. Within-group variability in all measurements was also compared.

Results

The search identified 43 eligible studies. Compared to people without LBP, on average, people with LBP display: (i) no difference in lordosis angle (8 studies), (ii) reduced lumbar ROM (19 studies), (iii) no difference in lumbar relative to hip contribution to end-range flexion (4 studies), (iv) no difference in standing pelvic tilt angle (3 studies), (v) slower movement (8 studies), and (vi) reduced proprioception (17 studies). Movement variability appeared greater for people with LBP for flexion, lateral flexion and rotation ROM, and movement speed, but not for other movement characteristics. Considerable heterogeneity exists between studies, including a lack of detail or standardization between studies on the criteria used to define participants as people with LBP (cases) or without LBP (controls).

Conclusions

On average, people with LBP have reduced lumbar ROM and proprioception, and move more slowly compared to people without LBP. Whether these deficits exist prior to LBP onset is unknown.

3.2.2. Background

Observation of lumbo-pelvic movement and posture is a basic component of the physical examination of people with low back pain (LBP) (Liebenson, C, 2007; Maitland, GD, 1986; McKenzie, R et al., 2003b; Sahrmann, S, 2002b) partly due to a common belief held by clinicians that identifying and correcting movement/postural aberration can improve pain and activity limitation (Ikeda, K et al., 2012; O'Sullivan, P. B., 2005; Sahrmann, S, 2002b). Examination of lumbo-pelvic movement typically includes basic kinematic assessments, such as range of movement (ROM) and posture. It may also include higher order kinematics such as temporal and sequential patterns during physiological movements, proprioception, muscle activation patterns, postural sway and/or complex functional movements such as walking or lifting. If clinicians aim to 'normalise' dysfunctional movement, they need an empirical basis for (i) differentiating between normal and dysfunctional movement, and (ii) determining whether correction of dysfunctional movement might reduce pain and activity limitation. Measurement of movement and posture has been problematic in typical clinical settings due to limitations (practicality, accuracy, comprehensiveness, reliability) of simple measurement tools such as goniometers, tape measures and inclinometers (Chen, SP et al., 1997). Advances in technology are creating new opportunities, available for use in typical clinical settings, that measure comprehensive information about the relationship between movement/posture and pain (Ha, TH et al., 2012; Ribeiro, DC et al., 2011; Van Hoof, W et al., 2012).

Measurements reported in studies of lumbo-pelvic kinematics, such as ROM, vary considerably. This variability may be due to differences in measurement instruments or methods (Mannion, A et al., 1999), biological differences in true range of movements, or errors in measurements. Intolo et al., (2009), in a systematic review into the effect of age on ROM, performed a meta-analysis of mean scores for lumbar ROM for 20-29 year olds. Across studies, the lowest reported group mean score for flexion was $24\pm7^{\circ}$ (Milosavljevic, S et al., 2005) while the highest was $75\pm10^{\circ}$ (Russell, P et al., 1993). Similarly, mean scores for extension ranged from $13\pm8^{\circ}$ (Milosavljevic, S et al., 2005) to $41\pm10^{\circ}$ (Fitzgerald, G et al.,

1983). These large differences between studies are unlikely to be due to biological differences alone. Milosavljevic et al (2005) provided ROM estimates using a photographic method, Russell et al (1993) used an Isotrak system and Fitzgerald et al (1983) used a tape-measure (Schober) method (Schober, P, 1937); such method differences are likely to account for a large proportion of observed differences. Similar variation is seen for axial rotation and lateral flexion movements. Extreme variations in reported ROM measurements limit confidence in clinical interpretations or treatment decisions based on measurements of an individual.

A search for reviews on what is known about typical movement in people with and without LBP identified one review on postural sway (Ruhe, A et al., 2011), and one review on age-related changes to lumbar spine ROM (Intolo, P et al., 2009). This qualitative review on postural sway, reported that 14 of 16 included papers concluded that people with LBP have greater postural sway excursion when compared to people without LBP. The review on age-related change to lumbar ROM reported a reduction in ROM associated with increasing age but did not include people with LBP and did not report mean ROM data. No reviews were found comparing people with and without LBP on any other movement characteristics. Therefore, we designed this review to systematically investigate and compare typical lumbo-pelvic movement differences between people with and without LBP, focusing on ROM, movement sequence and speed, a movement related measure of proprioception (positioning/re-positioning accuracy), pelvic tilt angles (in standing and sitting), and segmental body contributions to movement (lumbar versus hip contributions). We also compared differences in variability between the two groups.

3.2.3.   Methods

Study selection: inclusion and exclusion criteria

For inclusion in the review, studies had to (i) assess adults >17 years; (ii) use non-invasive measurement systems (i.e. did not use measurements such as X-rays, CT scans); (iii) apply the same procedures to measure people with low back +/-leg pain (LBP group) and people without LBP (NoLBP group), (iv) measure at least one of lumbar lordosis, lumbar range of motion (ROM), speed/acceleration/timing of lumbar +/- hip movement, pelvic tilt angle (as measured by a line drawn from anterior to posterior superior iliac spines with an angle formed relative to horizontal, measured in sitting or standing), pelvic tilt ROM (defined as a range from maximum anterior tilt to maximum posterior tilt), usual sitting pelvic tilt position (i.e. relative to full anterior tilt), lumbar compared with hip

contributions to ROM, lumbo-pelvic proprioceptive position/re-position accuracy; (v) report appropriate measurement means (or other point estimates) and variance estimates or data that enable estimation of these values. In order to fully survey published research on lumbo-pelvic movement, no specific definitions of back pain or control (NoLBP) groups were required but the definitions of LBP group, pain intensity and NoLBP group within each study were extracted. Studies were excluded if they (i) included people who had lumbar surgery in the previous 12 months; (ii) reported that subjects had fracture, neurological conditions, metabolic disease, neoplasm, or scoliosis; (iii) measured only whole body movement such as distance from finger-tip-to-floor or (iv) reported insufficient data, e.g. did not report measures of variability. Lead authors were contacted to obtain additional data as required.

Data sources

Eight electronic databases (MEDLINE, Cochrane Central Register of Controlled Trials (Central), EMBASE, AMI, CINAHL, Scopus, AMED, ISI Web of Science) were searched from inception until January 2014 using a broad search strategy based on relevant medical subject heading (MeSH) terms (USA, NLoM, 2012) (see Appendix E). The search yield was initially screened for eligibility by one reviewer (RL) on title and abstract to remove duplicates and clearly unrelated articles. Following this, two reviewers (RL and JG) independently identified potentially relevant articles based on title and abstract. Full text articles were retrieved and checked for compliance with inclusion and exclusion criteria. References of potentially relevant reports were reviewed for additional papers. Consensus by discussion was then reached on article inclusion. Where disagreement occurred, a third reviewer (JK) was included and discussion continued until consensus was achieved. A flow diagram of the study selection process based on PRISMA recommendations (Moher, D et al., 2009) is seen in Figure 1.

Data extraction and study quality assessment

A checklist for data extraction was developed based on those used in a similar review (Intolo, P et al., 2009) and published quality assessment tools (Bossuyt, PM et al., 2003; Hollingworth, W et al., 2006; Whiting, PF et al., 2006). The following study details were extracted: participant age, sex, and source characteristics, inclusion/exclusion criteria, training of testers (profession, experience), measurement methods and procedures (instrument used, instructions to participants, position of testing), the movement characteristics assessed (e.g. range, speed, relative contributions of body segments), pain/function measures, measurements for those with and without back pain (e.g. means, standard

deviations). A quality assessment tool, using a similar approach to Mieritz et al (2012), was constructed to determine how each study accounted for possible sources of bias, and if the study provided details on: (i) study population (age, sex, BMI, source), (ii) participant LBP (chronicity, +/- leg pain, specific versus non-specific, pain intensity and activity limitation scores), (iii) measurement procedures (i.e. detail that would enable accurate replication of the experiment, instrument description, standardised movement instructions, movement process description e.g. fixed or free pelvis), (iv) blinding of assessors to the presence of back pain (yes/no), and (vi) whether the same assessment procedures were applied to participants with and without back pain (see Appendix F). Two reviewers independently extracted data, compared results and resolved differences through discussion.

Data synthesis and analysis

Study details were extracted and summarised (Appendix G and H). For each comparison, standardised mean differences (SMD) between groups with and without LBP were calculated using Revman software ("Review Manager (RevMan) Version 5.2," 2012). Pooled estimates of overall differences were calculated by meta-analysis of studies that measured a kinematic characteristic using comparable methods. For example, studies on flexion ROM were included in a meta-analysis if subjects were standing using angular measurement but excluded if subjects were in other positions (i.e. four point kneeling) or if linear/distance measurements were used. Reasons for exclusion from meta-analysis are found in Appendix G. A random effects model was used for pooling where fixed effects modeling indicated statistical heterogeneity of the data (Mantel-Haenszel method), as determined by chi-squared and I^2 statistics; otherwise the results of fixed effects modeling was reported (Higgins, J et al., 2011; Higgins, J et al., 2003).

We also planned to explore the within-group variability in each measured movement characteristic. To estimate whether variability for each movement characteristic differed between groups with and without LBP, a coefficient of variation (CoV) (Koopmans, L et al., 1964) (standard deviation in measurements divided by the group mean) was calculated for each movement parameter using those studies included in the relevant meta-analysis. CoVs were averaged after weighting for sample size. Differences between groups were examined by creating a ratio of weighted averages where ratios >1 indicate greater variability for those with LBP and ratios <1 indicate greater variability for those without LBP. Significant differences in pooled CoVs were examined by estimating 95% confidence intervals for

observed ratios. The correlation (Pearson's r) between effect size and study quality was calculated using STATA (version 12, Stata Corp, College Station, Texas USA).

3.2.4. Results

Search yield

The search identified 17,276 potentially relevant articles with 13 articles identified from bibliographies of related articles or other sources. Following screening of title and abstract, full texts of 86 articles were retrieved. Forty three studies (45 articles) met the inclusion criteria (Aluko, A et al., 2011; Barrett, CJ et al., 1999; Boline, P et al., 1992; Christie, HJ et al., 1995; Crosbie, J et al., 2013; Day, JW et al., 1984; Descarreaux, M et al., 2005b; Esola, MA et al., 1996; Field, E et al., 1997; Georgy, E, 2011a; Gill, K et al., 1998; Gomez, TT, 1994; Hidalgo, B et al., 2012; Hidalgo, B et al., 2013; Hultman, G et al., 1993; Kim, MH et al., 2013; Koumantakis, George A. et al., 2002; Lee, AS et al., 2010; Marras, W et al., 1995; McClure, P et al., 1997; McGregor, A et al., 1997a; McGregor, A et al., 1995; McGregor, AH et al., 2000; Mellin, G, 1990; Newcomer, K et al., 2000; Newcomer, KL et al., 2000; Ng, JK et al., 2002; Norton, B et al., 2004; Nourbakhsh, MR et al., 2001; O'Sullivan, K et al., 2013; O'Sullivan, PB et al., 2003; Paquet, N et al., 1994; Pope, M et al., 1985; Porter, JL et al., 1997; Sheeran, L et al., 2012; Sung, PS et al., 2012; Taimela, S et al., 1999; Tsai, Y et al., 2010; Waddell, G et al., 1992; Willigenburg, NW et al., 2013; Willigenburg, NW et al., 2012; Youdas, JW et al., 2000; Youdas, JW et al., 1996). The study selection process is shown in Figure 3.2. A summary of included studies can be seen in Appendix G. A list of studies retrieved in full text and subsequently excluded, and reasons for exclusion, are available from the first author on request.

```
┌─────────────────────────────────────────┐
│ Electronic Database search:              │
│  • Medline, Cochrane, AMED (via Ovid) 7137│
│  • Embase                           816  │
│  • Aust. Med. Index                  92  │
│  • Cinahl                           570  │
│  • Scopus                          4496  │
│  • ISI Web of Science              4165  │
│                                          │
│                        Total 17276       │
└─────────────────────────────────────────┘
                    │
                    ▼
          ┌───────────────────┐
          │ 9813 articles after│
          │ duplicates removed │
          └───────────────────┘
                    │
┌──────────────────┐│              ┌──────────────────┐
│ 13 additional    ││  9826        │      9740         │
│ articles         │▶│ articles     │▶│ articles excluded │
│ identified       ││ screened by  │ └──────────────────┘
│ through other    ││ title and    │
│ sources          ││ abstract     │
└──────────────────┘└──────────────┘
                    │
                    ▼
        ┌──────────────────────┐    ┌──────────────────────────────┐
        │ 86 full text articles│    │ articles excluded:           │
        │ retrieved and        │▶│  • Single cohort studies (30) │
        │ assessed for         │    │  • Differentiation between    │
        │ eligibility          │    │    LBP and normal subjects    │
        └──────────────────────┘    │    poor (1)                   │
                    │               │  • Post surgical subjects (1) │
                    │               │  • Insufficient data (5)      │
                    ▼               │  • Hip movement only (1)      │
        ┌──────────────────────┐    │  • Participants < 17 years (3)│
        │ 45 articles (43      │    └──────────────────────────────┘
        │ studies) included    │
        │ in review            │
        └──────────────────────┘
                    │
                    ▼
        ┌──────────────────────┐
        │ 35 studies included  │
        │ in meta-analysis     │
        └──────────────────────┘
```

Figure 3.2 Flow diagram of study inclusion

Types of studies found

Included studies were grouped in categories: lordosis (Christie, HJ et al., 1995; Day, JW et al., 1984;

Hultman, G et al., 1993; Ng, JK et al., 2002; Norton, B et al., 2004; Nourbakhsh, MR et al., 2001;

Youdas, JW et al., 2000; Youdas, JW et al., 1996), range of movement (ROM) (Barrett, CJ et al., 1999;

Boline, P et al., 1992; Crosbie, J et al., 2013; Esola, MA et al., 1996; Hidalgo, B et al., 2012; Hultman,

G et al., 1993; Marras, W et al., 1995; McClure, P et al., 1997; McGregor, A et al., 1997a; McGregor, A

et al., 1995; Mellin, G, 1990; Ng, JK et al., 2002; Paquet, N et al., 1994; Pope, M et al., 1985; Porter,

JL et al., 1997; Sheeran, L et al., 2012; Sung, PS et al., 2012; Tsai, Y et al., 2010; Waddell, G et al.,

1992; Wong, TK et al., 2004; Youdas, JW et al., 2000; Youdas, JW et al., 1996), relative hip and lumbar contribution to trunk flexion/extension (Esola, MA et al., 1996; Kim, MH et al., 2013; McClure, P et al., 1997; Paquet, N et al., 1994; Porter, JL et al., 1997; Wong, TK et al., 2004), pelvic angle/relative position and ROM (Christie, HJ et al., 1995; Day, JW et al., 1984; Youdas, JW et al., 2000; Youdas, JW et al., 1996), speed/acceleration of lumbar movement (Aluko, A et al., 2011; Esola, MA et al., 1996; Hidalgo, B et al., 2012; Marras, WS et al., 1995a; McGregor, A et al., 1997a; McGregor, A et al., 1995; Paquet, N et al., 1994; Wong, TK et al., 2004), and proprioception (repositioning accuracy) (Brumagne, S et al., 2000; Descarreaux, M et al., 2005b; Field, E et al., 1997; Georgy, E, 2011a; Gill, K et al., 1998; Hidalgo, B et al., 2013; Kim, MH et al., 2013; Koumantakis, George A. et al., 2002; Lee, AS et al., 2010; Newcomer, K et al., 2000; Newcomer, KL et al., 2000; O'Sullivan, K et al., 2013; O'Sullivan, PB et al., 2003; Sheeran, L et al., 2012; Taimela, S et al., 1999; Willigenburg, NW et al., 2013; Willigenburg, NW et al., 2012). Appendix H summarises the characteristics of included studies.

Definition of LBP and NoLBP groups

Case definition (LBP)

Of the 43 studies included, 48% provide no detail on diagnostic criteria, 37% defined their LBP participants as non-specific, and the remaining 15% used either a Quebec (Spitzer, WO et al., 1987) or a movement based classification (see Appendix I for details). Fifty-six percent reported pain intensity scores.

Control definition (NoLBP)

A definition of control participants was provided by 60% of the 43 studies. Those definitions were highly variable, ranging from vague descriptions such as 'no current pain' (16%), six-months (14%), 12-months (14%) or 24-months (7%) pain free to 'no LBP ever' (9%).

Quality Assessment

Table 3.1 lists the domains identified as potential sources of bias in the included studies and the percentage compliance with each item. No studies attempted blinding of assessors to group status, and only one study reported standardizing instructions to participants. The potential influence of study quality on reported differences between groups was examined for all groups. There was no significant

correlation observed between total quality assessment scores and the magnitude of SMDs in measurements for those with and without LBP (r=0.03), There was also no significant difference between individual items of quality assessment and the size of SMD. Results for individual studies are available in Appendix I.

	Quality assessment domains	Percentage of studies scoring yes
	Selection bias	
1	Was the study population adequately described?	57%
2	Where both groups drawn from the same population?	39%
3	Were both groups comparable for age, sex, BMI/weight	54%
4	Was pain intensity and/or activity limitation described for LBP group?	56%
5	Was an attempt made to define back pain characteristics?	34%
	Measurement and outcome bias	
6	Did the method description enable accurate replication of the measurement procedures	90%
7	Was the measurement instrument adequately described?	95%
8	Was a system for standardising movement instructions reported?	37%
9	Were assessors trained in standardised measurement procedure?	2%
10	Did the same assessors test those with and without back pain	17%
11	Were assessors blinded as to which group subjects were in?	0%
12	Was the same assessment procedure applied to those with and without back pain?	93%
	Data presentation	
13	Were between-group statistical comparisons reported for at least one key outcome	94%

Table 3.1 Quality assessment summary (see Appendix F and I for item decision rules and scores for each included study)

Movement Characteristics

Lordosis

A meta-analysis of eight studies comparing lumbar lordosis angle in people with and without LBP when standing is presented in Figure 3.3. Most studies reported small, non-significant differences between groups. The pooled difference (SMD=0.01, 95%CI -0.09 to 0.11, p=0.89) was not significant. A post-hoc meta-analysis of three studies that compared genders indicated that women had greater lordosis angles than men (SMD=0.92, 95%CI 0.8 to 1.05, p<0.01).

Study or Subgroup	LBP Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Christie ALBP 1995	22.6	7.9	20	19.3	9.2	10	1.8%	0.38 [-0.38, 1.15]
Christie CLBP 1995	26.4	9	19	19.3	9.2	10	1.6%	0.76 [-0.03, 1.56]
Day 1984	0.062	0.019	15	0.072	0.023	32	2.7%	-0.45 [-1.07, 0.17]
Hultman 1993	23.9	6.7	21	27.1	7.4	38	3.5%	-0.44 [-0.98, 0.10]
Ng 2002	26	9	15	25	8	15	2.0%	0.11 [-0.60, 0.83]
Norton 2004	42.5	15.2	128	40.2	14.8	60	10.9%	0.15 [-0.16, 0.46]
Nourbakhsh 2001	37	13	420	38	14	420	56.1%	-0.07 [-0.21, 0.06]
Waddell 1992	26.8	8.2	120	25.4	7.1	70	11.8%	0.18 [-0.12, 0.47]
Youdas 2000 Female	55.5	10.4	30	52.7	15.3	45	4.8%	0.20 [-0.26, 0.67]
Youdas 2000 Male	39	8.1	30	37.5	11	45	4.8%	0.15 [-0.31, 0.61]
Total (95% CI)			**818**			**745**	**100.0%**	**0.01 [-0.09, 0.11]**

Heterogeneity: Chi² = 13.81, df = 9 (P = 0.13); I² = 35%
Test for overall effect: Z = 0.13 (P = 0.89)

Figure 3.3 Studies comparing lordosis in LBP versus NoLBP groups

Means & standard deviations (SD) are in degrees with the exception of Day et al (Day, JW et al., 1984) who used an algebraic computation based on linear measurement.

Range of motion (ROM)

Meta-analyses of 26 ROM studies consistently found reduced range of movement of the lumbar spine in people with LBP. Figures 3.4-3.7 summarise the findings for flexion, extension, lateral flexion and rotation meta-analysis. Where studies measured bilateral movement, i.e. left and right rotation, weighted means and standard deviations were averaged. In some included studies, measurements

from a single group without LBP were compared with a number of LBP groups, such as men and women or acute and chronic LBP. As the observed differences may not satisfy the statistical assumption of independence required for meta-analysis (Marin-Martines, F et al., 1999), the sample size of these groups without LBP used in the meta-analysis were divided by the number of comparisons made. Means and standard deviations (SD) are in degrees of movement.

Study or Subgroup	LBP Mean	LBP SD	LBP Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Crosbie 2013	48	20	19	50	20	19	5.8%	-0.10 [-0.73, 0.54]
Esola 1996	40.3	14.1	20	43	10.3	21	5.9%	-0.22 [-0.83, 0.40]
Hidalgo 2012	69.4	16.8	25	92.2	14.9	25	5.9%	-1.41 [-2.04, -0.79]
Hultman 1993	41	7	21	48.7	8	38	6.1%	-0.99 [-1.56, -0.43]
Marras 1995	31.4	13.4	339	36	15	171	7.4%	-0.33 [-0.51, -0.14]
McGregor 1997	49.3	17.3	138	56.7	11.2	203	7.3%	-0.53 [-0.75, -0.31]
McGregor 2000	32	19	15	73	13	15	4.5%	-2.45 [-3.43, -1.47]
Mellin 1990 Female	43	8	29	40	8	19	6.0%	0.37 [-0.21, 0.95]
Mellin 1990 Male	27	6	26	27	8	29	6.3%	0.00 [-0.53, 0.53]
Ng 2002	51	13	15	50	10	15	5.5%	0.08 [-0.63, 0.80]
Porter 1997	57.5	9.1	15	68.6	9.2	17	5.3%	-1.18 [-1.94, -0.42]
Tsai 2010	56	12	16	55	11	16	5.6%	0.08 [-0.61, 0.78]
Waddell 1992	48.7	14.9	120	42.4	10.7	70	7.1%	0.46 [0.17, 0.76]
Wong 2004 LBP & +ive SLR	33.2	8.7	24	61.9	9.9	10	4.1%	-3.10 [-4.17, -2.02]
Wong 2004 LBP only	29.8	11.9	21	61.9	9.9	10	4.2%	-2.76 [-3.82, -1.71]
Youdas 2000 Female	20.7	8.9	30	23	10.1	45	6.5%	-0.24 [-0.70, 0.23]
Youdas 2000 Male	28.6	6.6	30	31	5.7	45	6.5%	-0.39 [-0.86, 0.08]
Total (95% CI)			903			768	100.0%	-0.62 [-0.94, -0.29]

Heterogeneity: Tau² = 0.36; Chi² = 126.26, df = 16 (P < 0.00001); I² = 87%
Test for overall effect: Z = 3.75 (P = 0.0002)

Less movt LBP vs NoLBP   More movt LBP vs NoLBP

Figure 3.4 Flexion ROM meta-analysis

Study or Subgroup	LBP Mean	LBP SD	LBP Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Hultman 1993	10.3	4.6	21	17.2	5.6	38	8.2%	-1.29 [-1.88, -0.71]
McGregor 1997	16.8	8.3	138	23.8	18.2	203	12.1%	-0.47 [-0.68, -0.25]
McGregor 2000	8	8	15	20.5	7	15	5.8%	-1.62 [-2.46, -0.78]
Mellin 1990 Female	43	8	29	40	8	19	8.2%	0.37 [-0.21, 0.95]
Mellin 1990 Male	39	8	26	44	9	29	8.6%	-0.58 [-1.12, -0.04]
Ng 2002	16	7	15	19	8	15	6.8%	-0.39 [-1.11, 0.34]
Tsai 2010	26	7	16	28	8	16	7.1%	-0.26 [-0.96, 0.44]
Waddell 1992	18.4	8	120	26.5	8.9	70	11.2%	-0.97 [-1.28, -0.66]
Wong 2004 LBP & +ive SLR	14.9	7.7	24	15.5	7.4	10	6.7%	-0.08 [-0.81, 0.66]
Wong 2004 LBP only	12.7	5.9	21	15.5	7.4	10	6.5%	-0.43 [-1.19, 0.34]
Youdas 2000 Female	56	12	30	56.5	10.4	45	9.5%	-0.04 [-0.51, 0.42]
Youdas 2000 Male	42.7	8.8	30	50.1	9.2	45	9.3%	-0.81 [-1.29, -0.33]
Total (95% CI)			485			515	100.0%	-0.54 [-0.81, -0.27]

Heterogeneity: Tau² = 0.15; Chi² = 37.67, df = 11 (P < 0.0001); I² = 71%
Test for overall effect: Z = 3.91 (P < 0.0001)

Less movt. LBP vs NoLBP   More movt. LBP vs NoLBP

Figure 3.5 Extension ROM meta-analysis

81

Study or Subgroup	LBP Mean	LBP SD	LBP Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Barrett 1999	24.5	6	23	28	5	31	10.1%	-0.63 [-1.19, -0.08]
Crosbie 2013	23	11	19	28	13	19	9.5%	-0.41 [-1.05, 0.24]
Marras 1995	3.5	2.8	339	3.3	2.7	171	12.1%	0.07 [-0.11, 0.26]
McGregor 1997	25.7	7.6	138	31.9	6.4	203	12.0%	-0.90 [-1.12, -0.67]
Mellin 1990	42.2	11.4	55	43.8	10	48	11.2%	-0.15 [-0.54, 0.24]
Ng 2002	29.5	5.5	15	31	15	55	10.0%	-0.11 [-0.68, 0.46]
Tsai 2010	37	6.5	16	41	6	16	9.0%	-0.62 [-1.34, 0.09]
Waddell 1992	22.7	7.6	120	29.4	6.5	70	11.6%	-0.92 [-1.23, -0.62]
Wong 2004 LBP & +ive SLR	11.8	4.3	24	23.7	5.4	10	7.2%	-2.51 [-3.48, -1.53]
Wong 2004 LBP only	12.8	4.7	21	23.7	5.4	10	7.4%	-2.15 [-3.10, -1.21]
Total (95% CI)			770			633	100.0%	-0.73 [-1.14, -0.33]

Heterogeneity: Tau² = 0.34; Chi² = 88.86, df = 9 (P < 0.00001); I² = 90%
Test for overall effect: Z = 3.55 (P = 0.0004)

Figure 3.6 Lateral flexion ROM meta-analysis

Study or Subgroup	LBP Mean	LBP SD	LBP Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Crosbie 2013	12	6	19	12	6	19	8.7%	0.00 [-0.64, 0.64]
Hidalgo 2012	50.6	12.4	25	61.6	10.3	25	9.4%	-0.95 [-1.54, -0.36]
Marras 1995	31.7	13.4	339	36	15	171	15.5%	-0.31 [-0.49, -0.12]
McGregor 1997	25.8	7.65	138	31.9	6.4	203	15.0%	-0.88 [-1.10, -0.65]
Ng 2002	27.5	6.5	15	30.5	10	15	7.7%	-0.35 [-1.07, 0.38]
Pope 1985	2.99	0.74	215	3.34	0.71	106	14.8%	-0.48 [-0.71, -0.24]
Sung 2012	14.58	5.5	15	10.06	4.5	15	7.3%	0.88 [0.12, 1.63]
Tsai 2010	43	5	16	47	7	16	7.8%	-0.64 [-1.35, 0.07]
Wong 2004 LBP & +ive SLR	7.3	3.7	24	12.2	4.6	10	6.9%	-1.20 [-2.00, -0.41]
Wong 2004 LBP only	9	3.4	21	12.2	4.6	10	7.0%	-0.82 [-1.60, -0.03]
Total (95% CI)			827			590	100.0%	-0.49 [-0.76, -0.22]

Heterogeneity: Tau² = 0.12; Chi² = 36.25, df = 9 (P < 0.0001); I² = 75%
Test for overall effect: Z = 3.54 (P = 0.0004)

Figure 3.7 Rotation ROM meta-analysis

Lumbar spine versus hip contribution to flexion/extension

Six studies examined the relative lumbar and hip contribution to flexion movements, five (Esola, MA et al., 1996; Kim, MH et al., 2013; Paquet, N et al., 1994; Porter, JL et al., 1997; Wong, TK et al., 2004) during forward flexion, and one (McClure, PW et al., 1997) returning from a fully flexed position. Four of five studies investigating forward flexion found no significant difference between those with and without LBP when comparing lumbar with hip contribution (ratio) to flexion ROM *at end range*. A non-significant but consistent effect favored reduced lumbar (compared with hip) contribution to flexion (Figure 3.8) for those with LBP (SMD= -0.21, 95%CI -0.52 to 0.09, p=0.17). Three studies (Esola, MA et al., 1996; McClure, PW et al., 1997; Porter, JL et al., 1997) found significant differences in the '*through-range*' contribution of lumbar movement. Esola et al (1996) (SMD=-0.86, 95%CI -1.51 to -0.22)

and Porter et al (1997) (SMD=-0.71 95%CI -1.43 to 0.00) both found significant reductions of lumbar contribution to mid-range flexion but not at end range. McClure et al (1997) found a greater contribution of the lumbar spine during mid-range return from the fully flexed position (relative extension) (SMD=0.95 95%CI 0.10 to 1.81).

Study or Subgroup	LBP Mean	SD	Total	NoLBP Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Esola 1996	0.64	0.25	20	0.65	0.29	21	24.6%	-0.04 [-0.65, 0.58]
Kim 2013 Extension LBP	0.8	0.7	14	0.9	0.7	8	12.2%	-0.14 [-1.01, 0.73]
Kim 2013 Flexion LBP	1.2	0.6	17	0.9	0.7	8	12.7%	0.46 [-0.39, 1.31]
Porter 1997	0.99	0.32	15	1.19	0.32	17	18.2%	-0.61 [-1.32, 0.10]
Wong 2004 LBP & +ive SLR	0.85	0.52	21	0.91	0.24	10	16.2%	-0.13 [-0.88, 0.62]
Wong 2004 LBP only	0.7	0.31	24	0.91	0.24	10	16.0%	-0.70 [-1.46, 0.06]
Total (95% CI)			111			74	100.0%	-0.21 [-0.52, 0.09]
Heterogeneity: Chi² = 5.57, df = 5 (P = 0.35); I² = 10%								
Test for overall effect: Z = 1.37 (P = 0.17)								

Figure 3.8 Lumbo-pelvic co-ordination (rhythm)

Meta-analysis of studies investigating the relative contributions of lumbar versus hip ROM through the range of trunk flexion. Means (and SDs) are ratios of lumbar to hip movement. Zero represents equal lumbar to hip contribution to trunk flexion, numbers <0 indicate less lumbar compared with hip movement while numbers >0 indicate more hip than lumbar movement.

Pelvic tilt angle, relative position and tilt range

Three studies (four articles) examined usual pelvic tilt angle in standing (Christie, HJ et al., 1995; Day, JW et al., 1984; Youdas, JW et al., 2000; Youdas, JW et al., 1996). No significant differences were found between people with or without LBP for any study (see Table 1 for details). A small, non-significant but consistent effect favouring greater anterior pelvic tilt in people with LBP was evident when studies were pooled in meta-analysis (see Figure 3.9). Only Day et al (1984) compared differences between groups with and without LBP in full anterior and posterior tilt positions, and found a significant difference for maximum anterior tilt angle (higher angle for people with LBP) : SMD=0.73 (0.09 to 1.35, p=0.02), but not maximum posterior tilt angle: SMD=0.09 (-0.53 to 0.7, p=0.78)).

Study or Subgroup	LBP Mean	LBP SD	LBP Total	No LBP Mean	No LBP SD	No LBP Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Christie CLBP 1995	12.8	8.8	19	10.7	9	20	17.4%	0.23 [-0.40, 0.86]
Day 1984	11	8.1	15	9.5	5.1	32	18.3%	0.24 [-0.38, 0.85]
Youdas 2000 Female	25	7.3	30	22.8	7.6	45	32.1%	0.29 [-0.17, 0.76]
Youdas 2000 Male	14.9	7.7	30	13.8	4.5	45	32.3%	0.18 [-0.28, 0.64]
Total (95% CI)			94			142	100.0%	0.24 [-0.03, 0.50]

Heterogeneity: Chi² = 0.11, df = 3 (P = 0.99); I² = 0%
Test for overall effect: Z = 1.76 (P = 0.08)
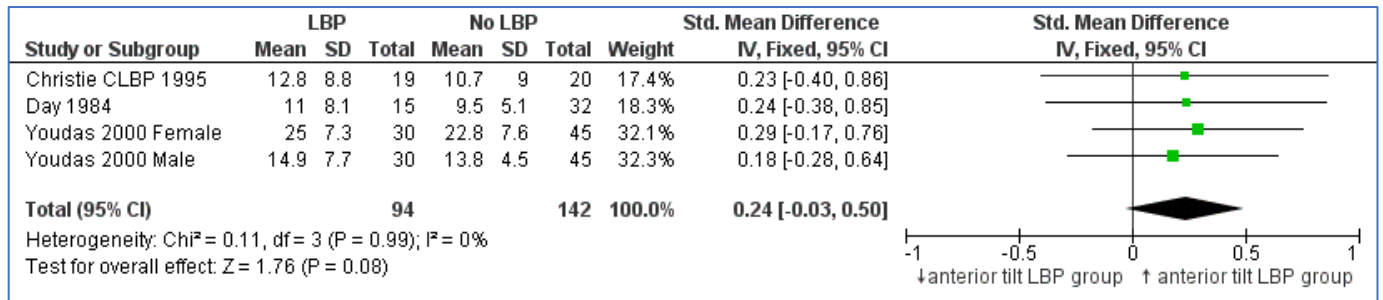
Figure 3.9 Meta-analysis of studies comparing pelvic tilt angle in neutral standing

Speed/Acceleration

Seven studies measured speed (Esola, MA et al., 1996; Hidalgo, B et al., 2012; Marras, W et al., 1995; McGregor, A et al., 1997b; McGregor, AH et al., 2000; Paquet, N et al., 1994; Wong, TK et al., 2004) and one measured acceleration (Aluko, A et al., 2011). Data on lumbar flexion speed/acceleration differences between groups with and without LBP were combined in meta-analysis (Figure 3.10). A large, significant effect of slower movement in the LBP group was evident (SMD -1.46 95%CI -1.96 to -1.02, p<.01).

Study or Subgroup	LBP Mean	LBP SD	LBP Total	No LBP Mean	No LBP SD	No LBP Total	Weight	Std. Mean Difference IV, Random, 95% CI
Aluko 2011	150.2	108.7	10	234.9	154.8	10	8.3%	-0.61 [-1.51, 0.29]
Esola 1996	35.94	11.07	20	41.78	12.58	21	11.9%	-0.48 [-1.10, 0.14]
Hidalgo 2012	117.6	34.3	25	159.3	40.8	25	12.3%	-1.09 [-1.69, -0.49]
Marras 1995	47.7	28.8	339	92	49	171	18.5%	-1.20 [-1.40, -1.00]
McGregor 1997	21.2	11.5	138	31.9	12.5	203	18.1%	-0.88 [-1.11, -0.66]
McGregor 2000	15	11	15	54	18	15	7.4%	-2.54 [-3.54, -1.55]
Paquet 1994	62	13	10	75	15	10	8.0%	-0.89 [-1.82, 0.04]
Wong 2004 LBP & +ive SLR	4.6	2.3	24	17.4	8.7	10	7.6%	-2.50 [-3.47, -1.52]
Wong 2004 LBP only	5.8	2.9	21	17.4	8.7	10	7.9%	-2.09 [-3.02, -1.15]
Total (95% CI)			602			475	100.0%	-1.24 [-1.58, -0.90]

Heterogeneity: Tau² = 0.15; Chi² = 30.02, df = 8 (P = 0.0002); I² = 73%
Test for overall effect: Z = 7.10 (P < 0.00001)

Figure 3.10 Forest plot of speed differences between LBP and NoLBP groups
(original units are deg/sec or deg/sec2)

Proprioception

Fifteen studies (Brumagne, S et al., 1999; Descarreaux, M et al., 2005b; Field, E et al., 1997; Georgy, E, 2011a; Gill, K et al., 1998; Hidalgo, B et al., 2013; Koumantakis, George A. et al., 2002; Lee, AS et al., 2010; Newcomer, K et al., 2000; Newcomer, KL et al., 2000; O'Sullivan, K et al., 2013; O'Sullivan, PB et al., 2003; Sheeran, L et al., 2012; Taimela, S et al., 1999; Willigenburg, NW et al., 2013; Willigenburg, NW et al., 2012) measured position/ reposition accuracy as a measure of lumbar spine proprioception (see Appendix J for further details). Twelve studies (Brumagne, S et al., 1999; Georgy, E, 2011a; Gill, K et al., 1998; Hidalgo, B et al., 2013; Koumantakis, George A. et al., 2002; Lee, AS et al., 2010; Newcomer, K et al., 2000; Newcomer, KL et al., 2000; O'Sullivan, K et al., 2013; O'Sullivan, PB et al., 2003; Sheeran, L et al., 2012; Tsai, Y et al., 2010) measured absolute error in re-positioning accuracy and were included in meta-analysis. One study measured the number of trials required to achieve accurate re-positioning (Descarreaux, M et al., 2005b), one measured motion detection, (Taimela, S et al., 1999) one measured ability to achieve a described position (Field, E et al., 1997) and two measured motion precision (Willigenburg, NW et al., 2013; Willigenburg, NW et al., 2012) but were excluded from meta-analysis as data were not comparable. A consistent, large and significant reduction in ability to accurately re-position the spine at pre-specified angles for people with LBP compared to those without LBP is shown in Figure 3.11 (SMD=1.04, 95%CI 0.64 to 1.45, p<0.01). The studies included in this review using different types of assessments that precluded meta-analysis also found significant differences indicating reduced proprioception in the LBP group. Descarreaux et al (2005b) tested if LBP subjects (divided into two groups according to normal or slow speed of force production on isometric resistance) compared to subjects without LBP, could accurately place the lumbar spine into various flexion angles. They determined that although both LBP and control groups demonstrated similar re-positioning accuracy, the LBP subgroup that developed slow isometric force (n=9 of 16) required significantly more practice to achieve this (SMD=1.87, 95%CI 0.89 to 2.85, p<0.01). Taimela et al (1999) reported a significant reduction in the ability of people with chronic LBP to detect change in lumbar position when compared to a group without LBP but did not include data on variability required for meta-analysis. Field et al (1997) demonstrated reduced accuracy for people with LBP in achieving a demonstrated position in flexion when compared to people without LBP (SMD=1.66, 95%CI 0.82 to 2.42, p<0.01). Willigenberg et al (2013, 2012) also identified reduced accuracy in both motion

control, (SMD=1.14, 95%CI 0.39 to 1.89, p<0.01) and motion tracking in people with LBP (SMD=1.08, 95%CI 0.32 to 1.84, p<0.01).

Study or Subgroup	LBP Mean	LBP SD	LBP Total	No LBP Mean	No LBP SD	No LBP Total	Weight	Std. Mean Difference IV, Random, 95% CI
Brumagne 2000 Sitting	4.3	1	23	1.6	0.6	21	6.6%	3.18 [2.27, 4.09]
Georgy 2011 Sitting	7.3	2.8	30	2.8	0.9	15	7.4%	1.88 [1.14, 2.62]
Gill 1998 Standing	6.7	5	20	4.5	3.4	20	8.0%	0.50 [-0.13, 1.13]
Hidalgo 2013 Sitting	4.3	2.6	10	1.8	2	10	6.4%	1.03 [0.09, 1.98]
Koumantakis 2002 Standing	5.5	3.5	62	3.7	1.8	18	8.5%	0.56 [0.02, 1.09]
Lee 2010 Sidelaying	1.3	1.1	24	0.7	0.4	24	8.2%	0.71 [0.13, 1.30]
Newcomer 2000a Standing	2.1	1.2	20	2.7	2	20	8.0%	-0.36 [-0.98, 0.27]
Newcomer 2000b Standing	5.1	2.2	20	3.4	2.2	20	7.9%	0.76 [0.11, 1.40]
OSullivan,K 2013 Sitting	11.5	6.4	15	5.1	3.6	15	7.2%	1.20 [0.41, 1.99]
OSullivan,P 2003 Sitting	1.7	0.8	15	1.1	0.6	15	7.4%	0.83 [0.08, 1.58]
Sheeran 2012 Sitting	7.7	4.1	90	1.8	0.8	17	8.3%	1.55 [0.99, 2.11]
Sheeran 2012 Standing	6.3	3.7	90	1.9	1	18	8.5%	1.28 [0.74, 1.81]
Tsai 2010 Standing	3.2	1.5	16	2.1	0.9	16	7.5%	0.87 [0.14, 1.60]
Total (95% CI)			435			229	100.0%	1.04 [0.64, 1.45]

Heterogeneity: Tau² = 0.43; Chi² = 57.03, df = 12 (P < 0.00001); I² = 79%
Test for overall effect: Z = 5.06 (P < 0.00001)

↑ proprioception LBP grp   ↓ proprioception LBP grp

Figure 3.11 Forest plot of proprioception differences between LBP and NoLBP groups

A summary of standardised mean differences, across all the kinematic characteristics investigated, is shown in Table 3.2.

Table 3.2 Summary of pooled standardized mean differences

Position and movement differences between people with and without LBP (number of studies included in meta-analysis)	Standardised mean difference (95%CI) for all studies suitable for meta-analysis
Lordosis*, n=8	0.01 (-0.09 to 0.11), p=0.89
Flexion**, n=14	-0.62 (-0.94 to -0.29), p<0.01
Extension**, n=9	-0.54 (-0.81 to -0.27), p<0.01
Lateral Flexion**, n=9	-0.73 (-1.14 to -0.33), p<0.01
Rotation**, n=9	-0.49 (-0.76 to -0.22), p=0.04
Lumbar versus Hip end-range flexion ROM** , n=4	-0.21 (-0.52 to 0.09), p=0.17
Pelvic tilt angle in standing†, n=3	0.24 (-0.03 to 0.50), p=0.08
Speed/Acceleration‡, n=8	-1.24 (-1.58 to -0.90), p<0.0001
Proprioception (re-position accuracy)§, n=12	1.04 (0.64 to 1.45), p<0.0001

*Positive numbers indicate larger lordosis for the LBP group, **negative numbers indicate reduced ROM for the LBP group, † positive numbers indicate larger anterior tilt, ‡ negative numbers indicate reduced speed of movement for the LBP group, § positive numbers indicate greater error rate in re-positioning (reduced proprioception)*

Differences in variability between groups

Table 3.3 presents a summary of the within group variability in movements pooled across studies. Significantly greater variability for people with LBP compared to people without LBP was observed on four of the eight measures: flexion, lateral flexion, rotation and speed/acceleration.

Table 3.3 Differences between the LBP and NoLBP in within-group variability on each movement characteristic and ratios of n-weighted mean coefficients of variation

Movement Characteristic (number of comparisons)	LBP group coefficient of variation	N	NoLBP group coefficient of variation	n	Ratio of coefficients of variation (95%CI)
Lordosis angle (8)	33.1%	818	34.6%	745	0.96 (0.83 to 1.10)
Flexion ROM* (18)	35.1%	913	26.8%	778	**1.31 (1.13 to 1.51)**
Extension ROM (12)	41.5%	485	47.2%	515	0.88 (0.76 to 1.01)
Lateral flexion ROM (9)	52.6%	751	40.1%	614	**1.31 (1.17 to 1.48)**
Rotation ROM* (10)	34.3%	827	28.7%	590	**1.20 (1.02 to 1.40)**
Lumbar vs hip (6)	51.2%	111	42.8%	74	1.2 (0.87 to 1.65)
Speed / acceleration* (8)	54.7%	602	42.6%	475	**1.28 (1.13 to 1.46)**
Proprioception (13)	53.9%	435	53.2%	229	1.01 (0.87 to 1.18)

Statistically significant differences (95%CIs > 1.0) are bolded

3.2.5. Discussion

This review summarised the results of studies of lumbo-pelvic kinematics for people with and without LBP. Although the results will be unsurprising to most clinicians, it is the first review to meta-analyse and quantify the clinical observation that, on average, people with LBP have reduced lumbar ROM, move more slowly and have reduced proprioception compared to with those without LBP.

The review highlights the highly heterogenous nature of available studies, with six of nine meta-analyses indicating significant between study heterogeneity in results. Possible sources of heterogeneity between study outcomes include differences in definitions of back pain, control characteristics, LBP intensity, and instruments and methods for measuring movements. This heterogeneity confounds secondary analyses such as the influence of pain intensity on observed differences between people with and without LBP.

The lack of detail or standardized definition for control subjects is also problematic. For example, it is hypothetically possible that altered movement characteristics occur as a result of a LBP episode and persist after pain resolves. If this is the case, people that were pain free but with persistent altered movements, would have been eligible as control subjects for many of the included studies, provided the episode had been prior to the pain-free time period required for that study. This would have diluted differences between the groups. Similarly, it is not known if certain 'aberrant' movement characteristics exist prior to the onset of LBP and are risk factors for an episode of LBP, in which case these characteristics may have also been present in people classified in the included studies as control subjects.

No studies attempted to blind assessors to group type, and a general absence of procedural standardization, such as movement instruction or assessor consistency, exposes studies to the potential for random or systematic error. However, the relative consistency of the direction of results across studies adds credibility to the findings of this review, and observed effects appear large enough to be visible despite potential study limitations.

Lordosis

Lordosis angle does not differentiate people with and without LBP. A similarly wide range of group means were reported for those with LBP (23° to 56°) and without LBP (19° to 53°). This variability might be associated with the six different measurement methods, but may also reflect biological differences in sample ethnicity (Mosner, EA et al., 1989), age (Gelb, D et al., 1995) and sex (Nourbakhsh, MR et al., 2001; Youdas, JW et al., 2000; Youdas, JW et al., 1996). Increasing age has been associated with reduced lordosis in the sixth decade (Adams, MA et al., 2012; Amonoo-Kuofi, H, 1992; Gelb, D et al., 1995) and on average, females have a greater lordosis than males (Amonoo-Kuofi, H, 1992; Nourbakhsh, MR et al., 2001; Youdas, JW et al., 1996). Four studies included only males (Christie, HJ

et al., 1995; Day, JW et al., 1984; Hultman, G et al., 1993; Ng, JK et al., 2002) and it is perhaps understandable that these studies found the four lowest average lordosis angles. However, this variability in lordosis appears similar for people with and without LBP. Therefore, lumbar lordosis when measured using surface techniques, does not, on average, appear to discriminate between people with and without LBP.

Range and speed of motion

Clinicians commonly use ROM (Kent, PM et al., 2009) to assist in identifying patterns of dysfunction, and to monitor change. ROM has been extensively studied by invasive and non-invasive methods, but non-invasive measurement is better suited to routine clinical assessment. This review included 20 studies that compared ROM for those with and without LBP using skin-surface measurement. The pooled sample was large enough to be confident in the finding that people with LBP have reduced average lumbar ROM compared to those without LBP. The mean ROM reported for people without LBP is so variable that it has little reference value e.g. (considering all studies) flexion: min= 23°, max=92°; extension: min=15°, max=56°, lateral flexion: min=3°, max=44°; rotation: min=3°, max=62°. Large variations between studies suggest differences beyond those explained by biological variation and implicate method differences. Using flexion ROM as an example, 14 studies used nine different measurement devices ranging in sophistication from simple handheld inclinometers and flexible rulers to opto-electronic devices. Youdas et al., (1996, 2000) used a flexible rule measurement technique (mean lumbar flexion angle=23±10°) while Hidalgo et al (2012) used an opto-electronic system (92±15°); both studies used similar inclusion criteria, and the same starting position . Other method processes may also contribute to differences: two studies assessed range in sitting, 10 in relaxed standing, and two used some form of restricted movement (harness or fixed pelvic position). Based on these findings, normative data may have limited relevance to a clinical environment unless the same measurement methods used to obtain published data are also used in the clinical setting where they are applied. The lack of clarity about similarity between study populations and method details makes the use of pooled group-level estimates of movements, such as mean flexion ROM, unwise. However, these between-study differences did not obscure consistent within-study findings; eight of 14 studies of flexion demonstrated significantly less lumbar flexion for those with LBP and only one study found that lumbar flexion was significantly greater for those with LBP. These findings of large between study

differences in measurements, and consistent within study differences between those with and without LBP, are similar for the other movements analysed in this review.

Lower movement speed is commonly seen in people with LBP, so it is unsurprising to observe in our review that those with LBP demonstrated significantly slower speeds when the eight included studies were pooled in meta-analysis. Reduced speed of lumbar movement has been linked to fear of movement and has also been shown to persist after recovery (Thomas, JS et al., 2008).

Lumbar versus hip contribution to movement

Clinicians have reported assessing the relative contribution of lumbar and hip (during flexion and extension movements) to assist in determining subgroups within the LBP population that require specific treatment strategies (Nelson-Wong, E et al., 2012; O'Sullivan, P.B., 2005a). This review identified six studies that measured patterns and relative contributions to trunk flexion from the lumbar spine and hip joints, often described as 'lumbo-pelvic rhythm'. Data could be pooled for four studies (six comparisons) evaluating ROM of lumbar and hip contribution at end-range flexion. A typical pattern of lumbar versus hip movement for both groups showed less lumbar and greater hip ROM at end-range flexion, with small, non-significant differences of reduced lumbar contribution for the LBP group when compared to people without LBP.

However relative contributions of lumbar spine and hip to ROM may be less important than patterns of when and how movement takes place. Nelson-Wong et al (2012) recently reported that the relative timing of hip and lumbar movement when arising from a fully flexed position differentiated between people who do or do not develop back pain after two hours of standing. People who developed pain used a lumbar > hip initiation of movement (spine moves first followed by pelvic/hip movement) strategy on arising from the flexed position while non-pain developers used a hip >lumbar strategy (p=0.03). This finding is supported by McClure et al (1997), Esola et al (1996) and Porter et al (1997) who all reported relatively greater lumbar through-range contribution in people with LBP on flexion movement. It may be that people with LBP can be subgrouped by lumbo-pelvic rhythm. For example, Kim et al (2013) examined lumbo-pelvic rhythm by comparing two subgroups of people with LBP to a group of people without LBP. One subgroup had pain provoked by flexion/rotation activities and the other by extension/rotation activity. The flexion-aggravated group had significantly greater lumbar contribution to flexion compared to the normal and extension groups. The extension-aggravated group on the other

hand had a significant pattern of reduced lumbar contribution to flexion. Lumbar versus hip contributions to movement, particularly flexion, appear to have clinical relevance and warrant further exploration.

Pelvic tilt angle, position and range

Extreme (end-range) pelvic tilt angle in standing and sitting has been linked to back pain (Astfalck, RG et al., 2010; O'Sullivan, PB et al., 2006) but with limited evidence. Clinical interventions aiming to modify pelvic tilt angle to achieve more neutral positions are based on the assumption that there is a relationship between position and pain. There are few studies that explore the relationship between LBP and typical pelvic tilt range (from full anterior to full posterior tilt) and the relative position of pelvic tilt angle during sitting and standing in people with and without LBP. This review found no differences when pooling data from three studies that compared standing pelvic tilt angle in people with and without LBP. Similarly, Astfalk et al (2010) found no differences in average lumbar flexion angle in sitting (reflecting pelvic tilt position) when comparing adolescents with and without LBP (125.3±19.8° vs 130.6°±15.7 respectively). However significant differences were observed for lumbar flexion angle when adolescents with LBP were sub-grouped based on direction of movement that provoked pain. The flexion-provoked pain group had a significantly greater lumbar angle (135.6±16.9°, $p<0.05$) compared to those without LBP while the extension-provoked pain group had a significantly smaller lumbar angle (113.5±16.3°, $p<0.05$) when compared to those without LBP. Sub-grouping of a LBP population based on the relationship of aggravating activities and direction of painful movement may demonstrate associations between back pain and pelvic tilt angle / relative position.

Proprioception

Our meta-analysis of studies measuring one aspect of proprioception (absolute error during re-positioning trials) demonstrated a significant and large loss of re-positioning accuracy in the LBP group. The implications of reduced proprioception are that people with LBP are less 'movement-aware' with potentially reduced postural control. This is consistent with a recent systematic review on another aspect of proprioception, postural sway, by Ruhe et al (2011) who found that greater sway excursion and speed were present in people with LBP compared to people without back pain.

Differences in variability between people with and without LBP

Our assessment of differences in variability between people with and without LBP for nine movement characteristics demonstrated significantly greater variability for four movement characteristics: flexion, lateral flexion and rotation ROM, and speed of movement. There were no significant differences in variability for lordosis, extension ROM, lumbar versus hip contribution to movement or proprioception. It is not clear if the greater variability seen in the LBP group is clinically meaningful (10% difference in average variability estimates) but it raises a question of whether postures or activities performed using extremes of certain movement (e.g. excessive or restricted movement) may predispose people to LBP.

This review examined differences in group means for people with and without LBP. Given the high variability seen between studies, the small between-group differences compared with the high within-group differences, and the greater variability on some movement characteristics seen in the LBP group, these findings cast some doubt on whether an assessment of movements without reference to pain provides evidence of dysfunction at an individual patient level. The results neither endorse nor disqualify the role of movement assessment for (i) determining the relationship between movement and pain in individual patients, or (ii) monitoring changes in movement characteristics as a means of monitoring progress in individual patients and as an indication of the likelihood of their improvement (Hahne, AJ et al., 2004). Key questions also remain, including (a) are deficits such as reduced proprioception, reduced ROM and speed of movement a result or a cause of LBP, and (b) are these deficits present prior to the development of LBP?

Strengths and limitations

The strengths of this systematic review are the comprehensive search, the breadth of the movement characteristics included in the analysis, and that screening and data extraction were independently performed by two reviewers. In addition, the review only included studies that assessed people with and without LBP using the same within-study method, thereby removing method differences as an explanation for observed within-study differences.

The review also has limitations. We treated the data for people with LBP as if they were measurements of a homogenous group. It is possible that sub-grouping by using the relationship of pain to movement may increase the clinical utility of particular measurements. The findings in this review do not inform clinicians about whether changes in ROM, movement speed or proprioception will produce better

outcomes, or if changes in movement characteristics precede the onset of LBP or predispose to future recurrences. In addition, due to an absence of translation resources, only articles published in English were included and this may introduce a language, cultural and/or publication bias. To maximize the number of included studies, we did not place any restrictions on the criteria used to define pain cases versus pain-free controls. However, our broad inclusion criteria are likely to have weakened, rather than strengthened differences seen between people with and without LBP, and in the included studies, higher pain intensities had a weak correlation with increased differences between the these groups.

3.2.6. Conclusion

This paper systematically summarised what is known about differences in measurements of lumbo-pelvic movement for people with and without back pain. It included 43 studies and synthesised information on six movement characteristics: lordosis, ROM, lumbar versus hip contribution, pelvic tilt, speed and proprioception. The results show that compared to people without pain, on average, people with LBP display (i) no difference in their lordosis angle (8 studies), (ii) a reduction of lumbar ROM in all directions of movement (26 studies), (iii) no difference in lumbar versus hip ROM contribution to full flexion (4 studies), (iv) no difference in pelvic tilt angle in standing (3 studies), (v) slower lumbar movement (7 studies), and (vi) poorer proprioception on position-reposition accuracy (15 studies). There is greater movement variability for people with LBP for flexion, lateral flexion and rotation ROM, and speed of movement, but this is not apparent for other movement characteristics. So put simply, when considered collectively, people with LBP have reduced lumbar ROM, move more slowly and have reduced proprioception compared with people without low back pain.

Abbreviations
LBP = Low Back Pain
ROM = Range of motion
SMD = Standardised Mean Difference
NoLBP = people without low back pain

Competing interests

Authors' contributions

RL and JG contributed to data collection. RL and JG performed data inclusion and extraction with JK providing arbitration when required. All authors were involved in the design of the review, analysis and interpretation of data, drafting and revision of the manuscript, and gave approval of the final manuscript.

Acknowledgements

3.2.7.   Bibliography for Laird et al (2014)

Adams, M. A., Bogduk, N., Burton, K., & Dolan, P. (2012). *The biomechanics of back pain* (3rd ed.). Edinburgh: Churchill Livingston.

Aluko, A., DeSouza, L., & Peacock, J. (2011). Evaluation of trunk acceleration in healthy individuals and those with low back pain. *International Journal of Therapy and Rehabilitation, 18*(1), 18-25.

Amonoo-Kuofi, H. (1992). Changes in the lumbosacral angle, sacral inclination and the curvature of the lumbar spine during aging. *Acta Antatomica, 145*, 373-377.

Astfalck, R. G., O'Sullivan, P. B., Straker, L. M., Smith, A. J., Burnett, A., Caneiro, J. P., et al. (2010). Sitting postures and trunk muscle activity in adolescents with and without nonspecific chronic low back pain: an analysis based on subclassification. *Spine, 35*(14), 1387-1395.

Barrett, C. J., Singer, K. P., & Day, R. (1999). Assessment of combined movements of the lumbar spine in asymptomatic and low back pain subjects using a three-dimensional electromagnetic tracking system. *Manual Therapy, 4*(2), 94-99.

Boline, P., Keating, J., Haas, M., & Anderson, A. (1992). Interexaminer reliability and discriminant validity of inclinometric measurement of lumbar rotation in chronic low-back pain patients and subjects without low-back pain. *Spine, 17*(3), 335-338.

Bossuyt, P. M., Reitsma, J. B., Bruns, D. E., Gatsonis, C. A., Glatsonis, P. P., Irwig, L. M., et al. (2003). Towards complete and accurate reporting of studies of diagnostic accuracy: The STARD Initiative. *Radiology, 226*, 24-28.

Brumagne, S., Cordo, P., Lysens, R., Verschueren, S., & Swinnen, S. (2000). The role of paraspinal muscle spindles in lumbosacral position sense in individuals with and without low back pain. *Spine, 25*(8), 989-994.

Brumagne, S., Lysens, R., & Spaepen, A. (1999). Lumbosacral repositioning accuracy in standing posture: a combined electrogoniometric and videographic evaluation. *Clinical Biomechanics, 14*(5), 361-363.

Chen, S. P., Samo, D. G., Chen, E. H., Crampton, A. R., Conrad, K. M., Egan, L., et al. (1997). Reliability of three lumbar sagittal motion measurement methods: surface inclinometers. *Journal of Occupational & Environmental Medicine, 39*(3), 217-223.

Christie, H. J., Kumar, S., & Warren, S. A. (1995). Postural aberrations in low back pain. *Archives of Physical Medicine and Rehabilitation, 76*(3), 218-224.

Crosbie, J., de Faria Negrao Filho, R., Nascimento, D. P., & Ferreira, P. (2013). Coordination of spinal motion in the transverse and frontal planes during walking in people with and without recurrent low back pain. *Spine, 38*(5), E286-292.

Day, J. W., Smidt, G. L., & Lehmann, T. (1984). Effect of pelvic tilt on standing posture. *Physical Therapy, 64*(4), 510-516.

Descarreaux, M., Blouin, J.-S., & Teasdale, N. (2005). Repositioning accuracy and movement parameters in low back pain subjects and healthy control subjects. *European Spine Journal, 14*(2), 185-191.

Esola, M. A., McClure, P. W., Fitzgerald, G. K., & Siegler, S. (1996). Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain. *Spine, 21*(1), 71-78.

Field, E., Abdel-Moty, E., & Loudon, J. (1997). The effect of back injury and load on ability to replicate a novel posture. *Journal of Back and Musculoskeletal Rehabilitation, 8*(3), 199-207.

Fitzgerald, G., Wynveen, K., Rheault, W., & Rothschild, B. (1983). Objective assessment with establishment of normal values for lumbar spinal range of motion. *Physical Therapy, 63*(11), 1776-1781.

Gelb, D., Lenke, L., Bridwell, K., Blanke, K., & McEnery, K. (1995). An Analysis of Sagittal Spinal Alignment in 100 Asymptomatic Middle and Older Aged Volunteers. *Spine, 20*(12), 1351-1358.

Georgy, E. (2011). Lumbar repositioning accuracy as a measure of proprioception in patients with back dysfunction and healthy controls. *Asian Spine Journal, 5*(4).

Gill, K., & Callaghan, M. (1998). The measurement of lumbar proprioception in individuals with and without low back pain. *Spine, 23*(3), 371-377.

Gomez, T. T. (1994). Symmetry of lumbar rotation and lateral flexion range of motion and isometric strength in subjects with and without low back pain. *Journal of Orthopaedic and Sports Physical Therapy, 19*(1), 42-48.

Ha, T. H., Saber-Sheikh, K., Moore, A. P., & Jones, M. P. (2012). Measurement of lumbar spine range of movement and coupled motion using inertial sensors - A protocol validity study. *Manual Therapy*.

Hahne, A. J., Keating, J. L., & Wilson, S. C. (2004). Do within-session changes in pain intensity and range of motion predict between-session changes in patients with low back pain? *Australian Journal of Physiotherapy, 50*(1), 17-23.

Hidalgo, B., Gilliaux, M., Poncin, W., & Detrembleur, C. (2012). Reliability and validity of a kinematic spine model during active trunk movement in healthy subjects and patients with chronic non-specific low back pain. *Journal of Rehabilitation Medicine, 44*(9), 756-763.

Hidalgo, B., Gobert, F., Bragard, D., & Detrembleur, C. (2013). Effects of proprioceptive disruption on lumbar spine repositioning error in a trunk forward bending task. *Journal of Back & Musculoskeletal Rehabilitation, 26*(4), 381-387.

Higgins, J., & Green, S. (2011). *Cochrane Handbook for Systematic Reviews of Interventions, Version 5.1.0*

Higgins, J., Thompson, S., Deeks, J., & Altman, D. G. (2003). Measuring inconsistency in meta-analyses. *British Medical Journal (Clinical Research Ed.), 327*(9), 557-560.

Hollingworth, W., Medina, S., Lenkinski, R., Shibata, D., Bernal, B., Zurakowski, D., et al. (2006). Interrater reliability in assessing quality of diagnostic accuracy studies using the QUADAS tool. *Academic Radiology, 13*(7), 803-810.

Hultman, G., Nordin, M., Saraste, H., & Ohlsen, H. (1993). Body composition, endurance, strength, corss-sectional area, and desnity of MM erector spinae in men with and without low back pain. *Journal of Spinal Disorders, 6*, 114-123.

Ikeda, K., & McGill, S. (2012). Can altering motions, postures, and loads provide immediate low back pain relief: A study of 4 cases investigating spine load, posture, and stability. *Spine, 37*(23), E1469-1475.

Intolo, P., Milosavljevic, S., Baxter, D. G., Carman, A. B., Pal, P., Munn, J., et al. (2009). The effect of age on lumbar range of motion: a systematic review. *Manual Therapy, 14*(6), 596-604.

Kent, P. M., Keating, J. L., & Taylor, N. F. (2009). Primary care clinicians use variable methods to assess acute nonspecific low back pain and usually focus on impairments. *Manual Therapy, 14*(1), 88-100.

Kim, M. H., Yi, C. H., Kwon, O. Y., Cho, S. H., Cynn, H. S., Kim, Y. H., et al. (2013). Comparison of lumbopelvic rhythm and flexion-relaxation response between 2 different low back pain subtypes. *Spine, 38*(15), 1260-1267.

Koopmans, L., Owen, D., & Rosenblatt, J. (1964). Confidence intervals for the coefficient of variation for the normal and log normal distributions. *Biometrika, 51*, 25-32.

Koumantakis, G. A., Winstanley, J., & Oldham, J. A. (2002). Thoracolumbar proprioception in individuals with and without low back pain: intratester reliability, clinical applicability, and validity. *Journal of Orthopaedic and Sports Physical Therapy, 32*(7), 327-335.

Lee, A. S., Cholewicki, J., Reeves, N. P., Zazulak, B. T., & Mysliwiec, L. W. (2010). Comparison of Trunk Proprioception Between Patients With Low Back Pain and Healthy Controls. *Archives of Physical Medicine and Rehabilitation, 91*(9), 1327-1331.

Liebenson, C. (2007). *Rehabilitation of the spine : a practitioner's manual* (2nd ed.). Baltimore: Lippincott Williams & Wilkins.

Maitland, G. D. (1986). *Vertebral manipulation.* (5th ed.). London: Butterworths.

Mannion, A., & Troke, M. (1999). A comparison of two motion analysis devices used in the measurement of lumbar spinal mobility. *Clinical Biomechanics, 14*(9), 612-619.

Marin-Martines, F., & Sanchez-Meca, J. (1999). Averaging dependent effect sizes in meta-analysis: a coutionary note about procedures. *The Spanish Journal of Psychology, 2*(1), 32-38.

Marras, W., PaParnianpour, M., Ferguson, S., Kim, J., Crowell, R., Bose, S., et al. (1995). The classification of anatomic- and symptom-based low back disorders using motion measure models. *Spine, 20*(23), 2531-2546.

Marras, W. S., Parnianpour, M., Ferguson, S. A., Kim, J., Crowell, R. R., Bose, S., et al. (1995). The classification of anatomic- and symptom-based low back disorders using motion measure models. *Spine, 20*(23), 2531-2546.

McClure, P., Esola, M., Schreier, R., & Siegler, S. (1997). Kinematic analysis of lumbar and hip motion while rising from a forward, flexed position in patients with and without a history of low back pain. *Spine, 22*(5), 552-558.

McClure, P. W., Esola, M., Schreier, R., & Siegler, S. (1997). Kinematic analysis of lumbar and hip motion while rising from a forward, flexed position in patients with and without a history of low back pain. *Spine, 22*(5), 552-558.

McGregor, A., McCarthy, I., Dore, C., & Hughes, S. (1997). Quantitative assessment of the motion of the lumbar spine in the low back pain population and the effect of different spinal pathologies on this motion. *European Spine Journal, 6*(5), 308-315.

McGregor, A., McCarthy, I., & Hughes, S. (1995). Motion characteristics of the lumbar spine in the normal population. *Spine, 20*(22), 2421-2428.

McGregor, A., McCarthy, I., & Hughes, S. (1997). Lumbar spine motion during freestyle lifting and changes in this motion with time. *Journal of Back and Musculoskeletal Rehabilitation, 9*(1), 35-37.

McGregor, A. H., & Hughes, S. P. (2000). The effect of test speed on the motion characteristics of the lumbar spine during an A-P flexion-extension test. *Journal of Back and Musculoskeletal Rehabilitation, 14*(3), 99-104.

McKenzie, R., & May, S. (2003). *Lumbar Spine, Mechanical Diagnosis and Therapy.* (2nd ed.). Waikanae, New Zealand: Spinal Publications Ltd.

Mellin, G. (1990). Decreased joint and spinal mobility associated with low back pain in young adults. *Journal of Spinal Disorders, 3*(3), 238-243.

Mieritz, R., Bronfort, G., Kawchuk, G., Breen, A., & Hartvigsen, J. (2012). Reliability and measurement error of 3-dimensional regional lumbar motion measures: a sytematic review. *Journal of Manipulative and Physiological Therapeutics, 35*(8), 645-656.

Milosavljevic, S., Milburn, P. D., & Knox, B. W. (2005). The influence of occupation on lumbar sagittal motion and posture. *Ergonomics, 48*(6), 657-667.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D., & (2009), T. P. G. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Ann Intern Med, 151*(4), 264-269.

Mosner, E. A., Bryan, J. M., Stull, M. A., & Shippee, R. (1989). A comparison of actual and apparent lumbar lordosis in black and white adult females. *Spine, 14*(3), 310-314.

Nelson-Wong, E., Brendon, A., Csepe, D., Lancaster, D., & Callaghan, J. P. (2012). Altered muscle recruitment during extension from trunk flexion in low back pain developers. *Clinical Biomechanics, 27*, 994-998.

Newcomer, K., Laskowski, E., Yu, B., Larson, D., & An, K. (2000). Repositioning error in low back pain: Comparing trunk repositioning error in subjects with chronic low back pain and control subjects. *Spine, 25*(2), 245-250.

Newcomer, K. L., Laskowski, E. R., Yu, B., Johnson, J. C., & An, K. N. (2000). Differences in repositioning error among patients with low back pain compared with control subjects. *Spine, 25*(19), 2488-2493.

Ng, J. K., Richardson, C. A., Kippers, V., Parnianpour, M., Ng, J. K. F., Richardson, C. A., et al. (2002). Comparison of lumbar range of movement and lumbar lordosis in back pain patients and matched controls. *Journal of Rehabilitation Medicine, 34*(3), 109-113.

Norton, B., Sahrmann, S., & Van, D. L. (2004). Differences in Measurements of Lumbar Curvature Related to Gender and Low Back Pain. *Journal of Orthopaedic and Sports Physical Therapy, 34*(9), 524-534.

Nourbakhsh, M. R., Moussavi, S. J., & Salavati, M. (2001). Effects of lifestyle and work-related physical activity on the degree of lumbar lordosis and chronic low back pain in a Middle East population. *Journal of Spinal Disorders, 14*(4), 283-292.

O'Sullivan, K., Verschueren, S., Van Hoof, W., Ertanir, F., Martens, L., & Dankaerts, W. (2013). Lumbar repositioning error in sitting: Healthy controls versus people with sitting-related non-specific chronic low back pain (flexion pattern). *Manual Therapy, 18*(6), 526-532.

O'Sullivan, P. B. (2005). 'Clinical instability' of the lumbar spine: its pathological basis, diagnosis and conservative management. In J. Boyling & G. Jull (Eds.), *Grieve's Modern Manual Therapy - The Vertebral Column* (3rd ed.). Edinburgh: Churchill Livingstone.

O'Sullivan, P. B. (2005). Diagnosis and classification of chronic low backpain disorders: Maladaptive movement and motor control impairments as underlying mechanism. *Manual Therapy, 10*, 242-255.

O'Sullivan, P. B., Burnett, A., Floyd, A. N., Gadsdon, K., Logiudice, J., Miller, D., et al. (2003). Lumbar repositioning deficit in a specific low back pain population. *Spine, 28*(10), 1074-1079.

O'Sullivan, P. B., Mitchell, T., Bulich, P., Waller, R., & Holte, J. (2006). The relationship beween posture and back muscle endurance in industrial workers with flexion-related low back pain. *Manual Therapy, 11*(4), 264-271.

Paquet, N., Malouin, F., & Richards, C. (1994). Hip-spine movement interaction and muscle activation patterns during sagittal trunk movements in low back pain patients. *Spine, 15*(5), 596-603.

Pope, M., Bevins, T., Wilder, D., & Frymoyer, J. (1985). The relationship between anthropometric postural, muscular, and mobility characteristics of males aged 18-55. *Spine, 10*, 644-648.

Porter, J. L., & Wilkinson, A. (1997). Lumbar-hip flexion motion. A comparative study between asymptomatic and chronic low back pain in 18- to 36-year-old men. *Spine, 22*(13), 1508-1513; discussion 1513-1504.

. Review Manager (RevMan) Version 5.2 (Version 5.2). (2012) [computer program]. Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration.

Ribeiro, D. C., Sole, G., Abbott, J. H., & Milosavljevic, S. (2011). Cumulative postural exposure measured by a novel device: a preliminary study. *Ergonomics, 54*(9), 858-865.

Ruhe, A., Fejer, R., & Walker, B. (2011). Center of pressure excursion as a measure of balance performance in patients with non-specific low back pain compared to healthy controls: a systematic review of the literature. *European Spine Journal, 20*(3), 358-368.

Russell, P., Pearcy, M. J., & Unsworth, A. (1993). Measurement of the range and coupled movements observed in the lumbar spine. *Rheumatology, 32*(6), 490-497.

Sahrmann, S. (2002). Diagnosis and treatment of movement impairment syndromes.

.

Schober, P. (1937). The lumbar vertebral column and back ache. *Munchener Medizinische Wochenschrift, 84*, 336.

Sheeran, L., Sparkes, V., Caterson, B., Busse-Morris, M., & van Deursen, R. (2012). Spinal position sense and trunk muscle activity during sitting and standing in nonspecific chronic low back pain: classification analysis. *Spine, 37*(8), E486-495.

Spitzer, W. O., Arsenault, S., Abenhaim, L., Dupuis, M., Belanger, A., Bloch, R., et al. (1987). Quebec Task Force on spinal disorders - Scientific approach to the assessment and management of activity-related spinal disorders - a monograph for clinicians. *Spine, 12*(7), 1-59.

Sung, P. S., Park, W.-H., & Kim, Y. H. (2012). Three-dimensional kinematic lumbar spine motion analyses of trunk motion during axial rotation activities. *Journal of Spinal Disorders & Techniques, 25*(3), E74-80.

Taimela, S., Kankaanpaa, M., & Luoto, S. (1999). The effect of lumbar fatigue on the ability to sense a change in lumbar position. A controlled study. *Spine, 24*(13), 1322-1327.

Thomas, J. S., France, C. R., Lavender, S. A., & Johnson, M. R. (2008). Effects of fear of movement on spine velocity and acceleration after recovery from low back pain. *Spine, 33*, 564–570.

Tsai, Y., Sell, T., Smoliga, J., Myers, J., Learman, K., & Lephart, S. (2010). A comparison of physical characteristics and swing mechanics between golfers with and without a history of low back pain. *Journal of Orthopaedic and Sports Physical Therapy, 40*(7), 430-438.

USA, N. L. o. M. (2012). http://www.ncbi.nlm.nih.gov/mesh.

Van Hoof, W., Volkaerts, K., O'Sullivan, K., Verschueren, S., & Dankaerts, W. (2012). Comparing lower lumbar kinematics in cyclists with low back pain (flexion pattern) versus asymptomatic controls – field study using a wireless posture monitoring system. *Manual Therapy, 17*(4), 312-317.

Waddell, G., Somerville, D., Henderson, I., & Newton, M. (1992). Objective clinical evaluation of physical impairment in chronic low back pain. *Spine, 17*(6), 617-628.

Whiting, P. F., Weswood, M. E., Rutjes, A. W., Reitsma, J. B., Bossuyt, P. N., & Kleijnen, J. (2006). Evaluation of QUADAS, a tool for the quality assessment of diagnostic accuracy studies. *BMC Medical Research Methodology2006,, 6*(9), doi:10.1186/1471-2288-1186-1189.

Williigenburg, N. W., Kingma, I., Hoozemans, M. J. M., & van Dieen, J. H. (2013). Precision control of trunk movement in low back pain patients. *Human Movement Science, 32*(1), 228-239.

Williigenburg, N. W., Kingma, I., & van Dieen, J. H. (2012). Precision control of an upright trunk posture in low back pain patients. *Clinical Biomechanics, 27*(9), 866-871.

Wong, T. K., Lee, R. Y., Wong, T. K. T., & Lee, R. Y. W. (2004). Effects of low back pain on the relationship between the movements of the lumbar spine and hip. *Human Movement Science, 23*(1), 21-34.

Youdas, J. W., Garrett, T. R., Egan, K. S., & Therneau, T. M. (2000). Lumbar lordosis and pelvic inclination in adults with chronic low back pain. *Physical Therapy, 80*(3), 261-275.

Youdas, J. W., Garrett, T. R., Harmsen, S., Suman, V. J., & Carey, J. R. (1996). Lumbar lordosis and pelvic inclination of asymptomatic adults. *Physical Therapy, 76*(10), 1066-1081 (1030 ref).

3.3. Movement differences are seen for some lumbo-pelvic kinematic parameters

In this thesis, the first systematic review into relationships between changes in patterns of movement and changes in pain/activity limitation identified only 12 relevant trials. In contrast, the second review included 43 studies, indicating considerable clinical interest in measuring movement in people with persistent LBP. The second systematic review concluded that there ***are*** movement related differences in some but not all lumbo-pelvic kinematic parameters when comparing people with and without LBP. Methodological and measurement differences between the included studies make it very difficult to quantify these kinematic differences, other to than to say that, based on meta-analysis, people with LBP have significantly smaller lumbar ROM in sagittal, frontal and axial planes, slower movement speed and reduced proprioception accuracy than people without LBP.

Describing ROM lumbo-pelvic kinematic parameters

While some lumbo-pelvic kinematic parameters were commonly investigated, such as lordosis and lumbar ROM, other parameters were less commonly measured. As an example, Table 3.4 lists the 16 studies that measured lumbar ROM, with only five studies additionally reporting trunk and pelvic ROM, indicating that trunk and pelvic ROM components of movement have been less frequently investigated.

	Author, Date	Lumbar ROM	Trunk ROM	Hip ROM
1.	Crosbie, 2013	✔	✔	✔
2.	Esola, 1996	✔		✔
3.	Hidalgo, 2012	✔	✔	
4.	Hultman, 1992	✔	✔	
5.	Kim, 2013	✔		✔
6.	Marras, 1995	✔		
7.	McGregor, 1995,1997	✔		
8.	McGregor 2000	✔		
9.	Mellin 1990	✔	✔	✔
10.	Ng, 2002	✔		
11.	Pope, 1985	✔		
12.	Porter, 1997	✔	✔	✔
13.	Tsai, 2010	✔		
14.	Waddell, 1992	✔	✔	✔
15.	Wong, 2004	✔	✔	✔
16.	Youdas, 1996, 2000	✔		

Table 3.4: A comparison of articles included in Laird et al. (2014), detailing which ROM parameters were measured

Few studies compared lumbo-pelvic rhythm in people with and without LBP despite its potential clinical usefulness in classifying different types of movement disorders (Hoffman, SL et al., 2011; O'Sullivan, P.B., 2005b; Sahrmann, S, 2002a). Laird et al. (2014) analysed data on the peak angle values (i.e. ROM at maximum flexion) of lumbo-pelvic rhythm but not on other qualities of lumbo-pelvic rhythm such as the pattern (sequence) of through-range lumbar versus hip motion, the relative timing of each region, or the velocity of movement. Tsang et al. (2017) found that people without LBP could vary their patterns of lumbo-pelvic rhythm when they moved at different speeds, but people with LBP moved with the same strategy regardless of speed of bending. They did not find any differences in peak angles between groups, consistent with the results of this review.

'Higher order' lumbo-pelvic kinematic parameters were infrequently or rarely measured, suggesting lower clinical interest or greater difficulty associated with their measurement. Such parameters include regional (pelvic versus lumbar) timing, speed of movement and pelvic tilt angles and range (i.e. the range from full anterior to posterior tilt) in standing or sitting. Higher order lumbo-pelvic kinematic parameters are not generally included

as standard assessment procedures in clinical texts, are not part of typical assessment, are more difficult to measure, and require measurement tools that can accurately measure angular inclination of the spine over time.

3.3.1. Describing normal movement

It would have been ideal if this review could have assembled published data using meta-analysis to provide pooled estimates of 'normal' movement for each lumbo-pelvic kinematic parameter. However, the wide range of differing case/control definitions, methods and measurement tools, confounded simple comparisons between studies. Like the first review, the magnitude of mean scores (values) and differences for any given lumbo-pelvic kinematic parameter between people with and without LBP varied greatly between studies; some studies reported large differences, others reported small or no differences. Averaging the mean scores from the relevant studies for each parameter for people without LBP was considered to be unwise because the results could potentially be a highly inaccurate representation of measurements taken with different measurement methods or devices. Normative data for people without LBP could be very useful in identifying abnormal movement but it would require studies with large samples or pooled data from several studies that use the same or similar measuring instruments and methods. The concept of providing normative data is not new. In a large-scale study of lumbar ROM, Troke et al. (Troke, M et al., 2005; Troke, M et al., 2001) tested 405 asymptomatic subjects aged between 16 and 90 years of age using a CA-6000 Spine Motion Analyzer, a mechanical linkage instrument with 6 potentiometers (see Figure 3.12) that could measure three-dimensional movement. A sample of results from this study is seen in Figure 3.13, demonstrating the wide variance of lumbar flexion ROM and a decline in lumbar ROM with age.

Figure 3.12 The CA-6000 Spine Motion Analyzer application used to measure lumbar spine motion.

Image: reproduced with permission from: Mieritz, RM. (2013). Measuring regional movement in the lumbar spine: Reliability and change in chronic low back pain patients.(Thesis): http://findresearcher.sdu.dk:8080/portal/en/publications/measuring-regional-movement-in-the-lumbar-spine(f214fb37-2e57-49d6-bfba-b1584017e142).html
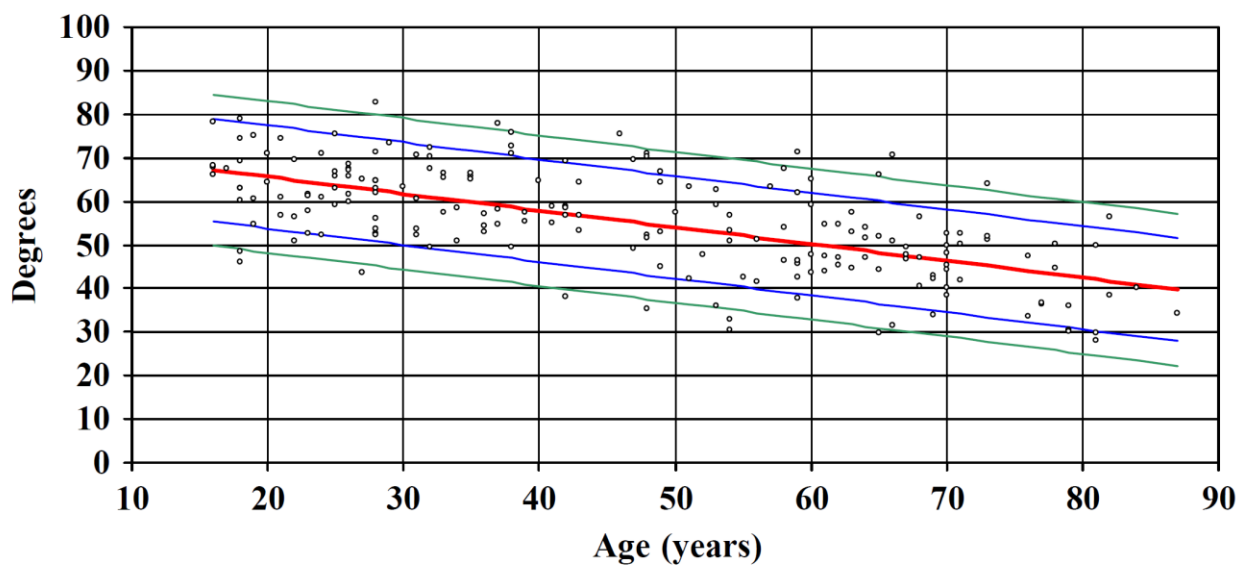
Figure 3.13 Flexion ROM in 196 asymptomatic females aged 16-90

(image reprinted from Troke, M., et al. (2005) with permission from Elselvier). The red line = 50th centile, blue= 10th and 90th centiles, green = 3rd and 97th centiles.

The reported data highlight some strengths and limitations of normative data. The use of large sample sizes increases the statistical power to observe age- and sex-related differences. However, the data for normative values seem to be more useful when the same measurement instrument and method are used. These issues are highlighted by comparing results from Dopf et al. (1994) and McGregor et al. (McGregor, AH et al., 1995). Both studies also used the same CA-6000 Spine Motion Analyzer device on people without a history of LBP but they used different methods. Dopf et al. recorded a mean lumbar flexion ROM of 81o (SD 10o) compared with McGregor et al. who reported mean lumbar flexion ROM as 55o (SD 10o). The study by Dopf et al. also compared the measurements of the CA6000 with those using a double inclinometer method with lumbar flexion ROM reported as 57o (SD 8o). This further demonstrates device-related differences in estimates.

The sample/control group definition of 'normal' is also a potential source of error. In order to be classified as 'normal', participants had to be pain-free at the time of data collection, and usually for a period prior to data collection. However, the pain-free period prior to data collection for 'normal' control subjects varied between studies. McGregor et al. (1995, p. 2422) defined normal as "no history of backache in the past 6 months". The authors reported that 29% of the 203 participants studied had a past history of LBP prior to the 6-month no-pain

definition, which may affect their findings if the included participants had any persistent altered movement as a result of previous back pain. There is some evidence that changes to movement can persist after LBP resolves (Ratzon, N et al., 2006; Smith, J et al., 2016), which supports the notion that different definitions of 'normal' or 'asymptomatic' might contribute to differences in observed mean ROM.

3.3.2. Variability of lumbo-pelvic kinematic parameters

Laird et al. (2014) also compared within-group variability of each lumbo-pelvic kinematic parameter in people with and without LBP, with greater variability seen in the LBP group for flexion, lateral flexion, rotation and speed of movement, but not extension, lordosis, lumbar versus hip contribution to movement or measurements of proprioception. The greater variability seen in the LBP group for some parameters, such as flexion ROM, may be because people with LBP could have either too much or too little ROM. People with LBP may demonstrate movements that are restricted for a range of reasons, such as increased muscle activation and co-contraction, or fear of movement. Other people may demonstrate excessive range of movement. Both increased (Hodges, PW et al., 2013; Sheeran, LP et al., 2012; Silfies, SP et al., 2009a) and decreased (Abboud, J et al., 2014; Claeys, K et al., 2011; Jacobs, JV et al., 2009; Lamoth, CJC et al., 2008; Moseley, GL et al., 2006) within-group variability have also been identified in other movement-related parameters, such as postural sway, and muscle activation patterns in LBP populations. These data align with the concept that people with LBP may have a range of movement deficits that fall in the 'too much' or 'too little' categories, and that there appear to be subgroups of people with specific movement-related patterns.

There is a clinical belief that people with LBP are heterogenous and that LBP is made up of more than one condition, with 74% of clinicians believing it is possible to recognise non-specific LBP subgroups (Kent, P et al., 2004). Some movement-related interventions have been designed to classify people into movement-based subgroups (McKenzie, R et al., 2003a; O'Sullivan, P. B., 2005; Sahrmann S., 2002). In the second systematic review of this thesis (Laird, R et al., 2014), most of the included studies did not subgroup LBP participants. One study did classify people with LBP into two subgroups using a combination of movement and pain provocation and found significant differences between the subgroups (Kim, MH et al., 2013). If individuals with LBP demonstrate considerable variability in movement, it is not unreasonable to think that there may be clusters or

subgroups of people who are distinguishable by patterns of lumbo-pelvic kinematic parameters or in related features such as pain direction, intensity or other factors. This concept is further explored in Chapter 6.

3.3.3.   Trends in measuring movement

The large body of research into movement-related parameters reflects the clinical view that movement parameters are related to LBP. However, there is little standardisation in assessing and measuring movement. Kent et al. (2009) surveyed 651 clinicians about their assessment of acute LBP. The authors reported that "*evaluation of lumbosacral ROM was the most commonly reported assessment, but only 10% of clinicians measured ROM very frequently or often*", and that "*most clinicians use visual estimation of ROM*" (p.93). Dijk et al. (2017) surveyed 114 clinicians about how they assessed movement quality in people with LBP. Ninety-nine percent of clinicians did not use a quantitative objective measure of lumbo-pelvic movement, with most clinicians using questionnaires, visual observation or timed movement tests. These data support the notion that assessing movement is considered important, but the methods of assessment are varied and usually quantified with estimates based on visual observation.

With the growth in the miniaturisation, ease of use and availability of inertial motion sensor technology, combined with advances in wireless communication and software development, a new generation of measurement tools using wireless motion sensor and EMG technologies are being used to measure lumbo-pelvic movement in clinical settings. The devices include the Vimove device (dorsaVi, Australia), the Valedo device (Hocoma, Switzerland), and Xsens MVN (Xsens, North America) systems that place electro-myographic sensors, accelerometers, gyroscopes and magnetometers into small units that are placed on the skin. The size of these units is sufficiently small to wear comfortably during normal activities of daily life, including during work and sport situations, as well as within clinical settings. These advances allow a transition from the clinical practice of visual observation or measurement approximations (such as measuring fingertip-to-floor distance to estimate trunk flexion ROM) to the use of technology-augmented assessment. They provide a range of standard (e.g. ROM) and higher order measurement details (e.g. timing and ROM of regional contributions, velocity and acceleration data, postural positions in standing and sitting, and patterns of movement and muscle activation) that are not easily measured with visual observation.

3.3.4. Inertial motion sensors can measure movement but there is little information about the reliability or consistency of measurements

There were no studies using inertial motion sensors identified by the review reported in this chapter, most likely due to the relatively recent development and availability of this type of technology. While motion sensor technology seems to have potential use in a clinical situation, data on its clinical reliability are a logical pre-requisite to determining if measurements of lumbopelvic kinematic parameters have clinical utility. Therefore, the next step was to test the reliability and consistency of lumbo-pelvic kinematic parameter measurements using wireless motion sensor technology within a typical clinical setting.

4. Chapter 4 – Do people with and without persistent LBP have consistent, repeatable range and patterns of movement when performing simple movements?

4.1. Introduction

Normal human movement is inherently variable. The combination of multiple sets of joints, muscles and neural pathways involved in movement create numerous options and strategies for performing a simple functional task, such as bending forwards.

While it is reasonable to assume that lumbo-pelvic kinematic parameters display some consistency across time, normal biological variation is highly likely. When measuring movement, additional sources of variation are introduced with error potentially arising from the measuring device, instructions, environmental conditions, effect of clothing or unanticipated sources. Measuring a movement repeatedly provides data on the expected variability or 'bandwidth' of scores. This 'bandwidth' will contain both biological variability and measurement error. A change of score outside of this bandwidth might then be attributed to some reason other than this expected normal variation. If lumbo-pelvic kinematic parameters are to be used as potential targets for therapeutic intervention, then data on the consistency (repeatability/stability) of each parameter are needed to determine whether any observed change to a movement parameter is expected normal variation or unexpected (and possibly real) change. Data on movement consistency, both within a single session and when measurements are repeated across days, have relevance to potential clinical applications.

Laird et al. (2014) highlighted the divergent results observed in measurements taken with different measurement devices and methods. The following study was designed to test the consistency and intra/inter tester reliability when using wireless inertial motion sensors (Vimove device, dorsaVi , Melbourne , Australia) in a typical clinical setting. Three different types of lumbo-pelvic kinematic parameters were measured; these were (i) standing lordosis (a relatively static postural parameter), (ii) ROM of the lumbar spine, trunk and pelvis (measured by angular inclination at T12 and S2), and (iii) lumbo-pelvic rhythm (a movement pattern-related parameter). Measurements were taken within session on the same day, and between sessions on different days.

Definitions for ROM measurements

The following information is provided in advance of the published study presented in 4.3 to ease the reader into understanding the definitions and device used (Laird, R et al., 2016), with a more detailed description within the paper. Further definitions and explanation of the lumbo-pelvic kinematic parameters used within this thesis are described in section 5.4.3.

The inertial motion sensors were placed at T12 and S2, and surface electromyographic (EMG) sensors placed at L2/3 intervertebral joint levels. Figure 4.1 (reproduced from Laird et al. (2016)) illustrates the device and its placement.

Figure 4.1 Placement of the Vimove sensors

Trunk ROM refers to angular inclination as measured by the inertial motion sensor placed at T12. Pelvic ROM refers to angular inclination of the sensor placed over S2. Lumbar ROM is constructed by subtracting pelvic motion from trunk motion. Both the T12 and S2 sensors are set to zero in the relaxed standing position. Therefore, following calibration of the sensors in the relaxed standing position, data from the T12 and S2

sensors would both signal 0°. As the participant moves from upright standing (where both T12 and S2 sensors equal 0°) to the fully flexed position, the gyroscope and accelerometers will generate information indicating the angular change and the speed of movement. In the fully flexed position, if the sensor placed at the level of the 12th thoracic vertebra (T12) records 100° and the sensor placed at the second sacral vertebra (S2) records 60°, then the ViMove device will register trunk angular displacement (trunk ROM) of 100°, pelvic angular displacement (pelvic ROM) of 60° and lumbar ROM, the difference between these two readings, would equal 40°. Details of other lumbo-pelvic kinematic parameters are available in section 5.4.3 and Appendix L.

4.2. Testing reliability and agreement when measuring lumbo-pelvic movement with inertial sensors

The following study "How consistent are lordosis, range of movement and lumbo-pelvic rhythm in people with and without LBP?" was published in BMC Musculoskeletal Disorders 2016. It has been viewed 2706 times and cited three times. The following section is an identical Word document version of Laird et al. (2016), reproduced within the thesis (section 4.3) to enable higher-quality text, suitable for printing if required. The published PDF version (see Figure 4.2) can be seen in Appendix K and an electronic copy of the PDF is available via open access at: https://bmcmusculoskeletdisord.biomedcentral.com/articles/10.1186/s12891-016-1250-1

RESEARCH ARTICLE

Open Access

CrossMark

How consistent are lordosis, range of movement and lumbo-pelvic rhythm in people with and without back pain?

Robert A. Laird[1,4*], Peter Kent[2,3] and Jennifer L. Keating[1]

Figure 4.2 The PDF version of this paper can be viewed in Appendix K

4.3. How consistent are lordosis, range of movement and lumbo-pelvic rhythm in people with and without back pain?

Robert A Laird[1]
Email:

Peter Kent[2,3]
Email:

Jennifer L Keating[1]
Email:

[1] Department of Physiotherapy, Monash University, PO Box 527, Frankston, Victoria 3199, Australia

[2] School of Physiotherapy and Exercise Science, Curtin University, Perth, Australia

[3] Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark

Postal Address:

[*] Corresponding author. Robert Laird, 380 Springvale Rd, Forest Hill, 3131 Melbourne, Victoria, Australia

4.3.1.   Abstract

Background

Comparing movements/postures in people with and without lower back pain (LBP) may assist identifying LBP-specific dysfunction and its relationship to pain or activity limitation. This study compared the consistency in lumbo-pelvic posture and movement (range and pattern) in people with and without chronic LBP (>12 week's duration).

Methods

Wireless, wearable, inertial measurement units measured lumbar lordosis angle, range of movement (ROM) and lumbo-pelvic rhythm in adults (n=63). Measurements were taken on three separate occasions: two tests on the same day with different raters and a third (intra-rater) test one to two weeks later. Participants performed five repetitions of tested postures or movements. Test data were captured automatically. Minimal detectable change scores (MDC$_{90}$) provided estimates of between-test consistency.

Results

There was no significant difference between participants with and without LBP for lordosis angle. There were significant differences for pelvic flexion ROM (LBP 60.8°, NoLBP 54.8°, $F_{(1,63)}$ =4.31, p = 0.04), lumbar right lateral flexion ROM (LBP 22.2°, NoLBP 24.6° $F_{(1,63)}$ = 4.48, p = .04), trunk right lateral flexion ROM (LBP 28.4°, NoLBP 31.7°, $F_{(1,63)}$= 5.9, p = .02) and lumbar contribution to lumbo-pelvic rhythm in the LBP group (LBP 45.8%, $F_{(1,63)}$ =4.20, NoLBP 51.3% p=.044). MDC$_{90}$ estimates for intra and inter-rater comparisons were 10°-15° for lumbar lordosis, and 5°-15° for most ROM. For lumbo-pelvic rhythm, we found 8%-15% variation in lumbar contribution to flexion and lateral flexion and 36%-56% variation in extension. Good to excellent agreement (reliability) was seen between raters (mean r =.88, ICC (2,2)).

Conclusion

Comparisons of ROM between people with and without LBP showed few differences between groups, with reduced relative lumbar contribution to trunk flexion. There was no difference between groups for lordosis. Wide, within-group differences were seen for both groups for ROM and lordosis. Due to variability between test occasions, changes would need to exceed 10°-15° for lumbar lordosis, 5°-15° for ROM components, and 8%-15% of lumbar contribution to lumbo-pelvic rhythm, to have 90% confidence that movements had actually changed. Lordosis, range of movement and lumbo-pelvic rhythm typically demonstrate variability between

same-day and different-day tests. This variability needs to be considered when interpreting posture and movement changes.

Keywords

Low back pain, movement disorders, posture, ROM, lordosis, lumbo-pelvic rhythm, reliability

4.3.2.   Background

In a recent 'Global Burden of Disease Study' (Vos, T et al., 2012), low back pain (LBP) was rated as the health condition responsible for the most years lived with disability when all common diseases were considered. Despite considerable research efforts, it is still unclear why some people recover from LBP pain and others do not, or how to match available interventions to care-seekers (Pincus, T et al., 2013). Many studies have focused on movement irregularities and patterns in LBP. Movement range has been used to monitor recovery status following interventions, and various patterns of movement have been investigated, including lumbar versus pelvic (hip) contribution to trunk movement (often called lumbo-pelvic rhythm) (Esola, MA et al., 1996; Lariviere, C et al., 2000; Lee, RYW et al., 2002; McClure, PW et al., 1997; Paquet, N et al., 1994; Porter, JL et al., 1997; Tafazzol, A et al., 2014). Opinions vary regarding the utility of measuring movement range and patterns. Nevertheless, many non-invasive interventions continue to target movement dysfunction in people with LBP.

A concept with current support is that individuals have consistent, and therefore recognisable, patterns of posture and movement, which may contribute to ongoing LBP (Ikeda, K et al., 2012; O'Sullivan, P.B., 2005b; Sahrmann, S, 2002b; Van Dillen, LR et al., 2003). Movement patterns such as excessive end range lumbar movements or postures (Pynt, J et al., 2008), excessive or reduced lumbar contribution to trunk flexion (Kim, MH et al., 2013), trunk rigidity (Hodges, PW et al., 2013), loss of flexion relaxation response (Neblett, R et al., 2010), and reduced proprioception (Brumagne, S et al., 2000; Descarreaux, M et al., 2005b), amongst others, have been linked to LBP. Recent research supports the concept that individualised approaches to modification of posture and movement patterns might reduce LBP (Kent, P et al., 2015b; Long, A et al., 2004). However, the relationship between specific movement characteristics/postures and LBP remains unclear. A recent systematic review of common movement characteristics in people with and without LBP concluded that people with LBP typically have reduced range of lumbar spine movement, move more slowly

and have reduced proprioception compared to people without LBP (Laird, R et al., 2014). Another recent review found only limited evidence for identifying and monitoring changes to movement patterns or postures (Laird, R et al., 2012).

Aberrant movement (range or patterns) and/or postures associated with LBP might be identifiable, provided these movements were consistent and could be accurately measured. Of particular clinical interest is the consistency of an individual's typical movement over short time periods (e.g. within a clinical session on the same day) and over longer time periods (e.g. one to two weeks apart). Common therapeutic targets of 'improving posture' and normalising dysfunctional movements are often influenced by within-session or between-session changes in movements following a treatment. Therefore, knowledge of the kinematic stability of movement patterns both within and between treatment sessions is important to clinicians who aim to identify, label and treat movement 'dysfunctions'. If movement/postural patterns normally fluctuate, and the variance in measures of movement/posture can be quantified, measurements outside the range of expected variation are likely to represent true movement alteration/adaptation. Those adaptive movements could be used to quantify response to treatment or to identify movements that either trigger, or are a response to, LBP.

Investigating the associations between movement and pain has been limited by difficulty in measuring and monitoring typical movement/posture both within clinical settings and in normal daily activity. Technological advances with movement sensors have enabled new opportunities to investigate the relationship between movement and pain (Bauer, CM et al., 2012; O'Sullivan, KJ et al., 2012; Ribeiro, DC et al., 2011). These devices are skin surface-mounted and generate data on lumbo-pelvic movements and postures, such as angle, timing, position and concurrent surface electromyography. There is preliminary evidence of high levels of accuracy relative to laboratory based opto-electronic measurement systems and they appear to have sufficient accuracy for clinical applications (Ha, TH et al., 2013; O'Sullivan, KJ et al., 2012).

This study investigated and compared consistency in lumbo-pelvic posture and movement (range and pattern) in people with and without chronic LBP (>12 week's duration). We examined the consistency (repeatability/measurement stability) of three types of lumbo-pelvic kinematic characteristics: (i) the postural characteristic of lordosis, (ii) range of movement (ROM) of flexion, extension, and lateral flexion, and (iii) lumbar compared to pelvic contributions to movement (lumbo-pelvic rhythm). Three types of movement consistency were of interest: 1) the consistency demonstrated when an individual repeats the same movement within a single test, 2) the consistency demonstrated when a person is tested twice by two

different raters on the same day, and 3) the consistency demonstrated when a person has a repeated test by the same person 7-14 days after the first test.

4.3.3.   Methods

Study selection: inclusion and exclusion criteria

Participants (with and without LBP) were recruited by poster and word-of-mouth advertising from private physiotherapy clinics and a university. People with LBP (LBP group) were included if they had back +/- leg pain for > 12 weeks and a pain score of > 2 on a 0 to 10 Numerical Rating Scale (average of worst, current, usual pain intensity) (Manniche, C et al., 1994). Exclusion criteria were any of the following: (i) previous lumbar surgery, (ii) any invasive spinal procedures for LBP, including therapeutic injections, within the last 12 months, (iii) pregnancy (iv) neoplasm, infection, fracture, inflammatory disease, neurological disease or any metabolic disorder that had the potential to affect the lumbo-pelvic region, (v) implanted electrical medical device, (vi) any medical abnormalities or conditions (e.g. knee or hip conditions) that in the opinion of the clinician would substantively interfere with an ability to participate in the study, (vii) a known allergic skin reaction to adhesive tapes or plasters, or (viii) BMI > 30 (where it becomes difficult to palpate bony landmarks). Participants recruited into the sample without back pain (NoLBP group) were excluded if they had (i) back pain at the time of testing, (ii) an episode of back pain that had necessitated attending a medical practitioner or allied health professional in the last 12 months, (iii) time off work due to back pain in the last 12 months or, (iv) any back pain during or between testing procedures. All potential participants were screened for suitability by a trained administrator, by direct contact and follow-up phone call if clarification was required, and then invited to participate. Ethics approval was obtained from Monash University (approval numberCF12/1995-20 12001090). All participants gave written informed consent.

Measurement protocol

Figure 4.3 presents the test procedures. Each participant was tested on two separate days. On the first test day, they were tested twice (Test 1 and Test 2) by two different raters (Raters A and B). On the second test day, they were assessed once (Test 3) by Rater A. On each test occasion, participants were assessed while they performed five repetitions of each movement. Data were collected at two geographic locations by physiotherapists with a minimum of two years' clinical experience.
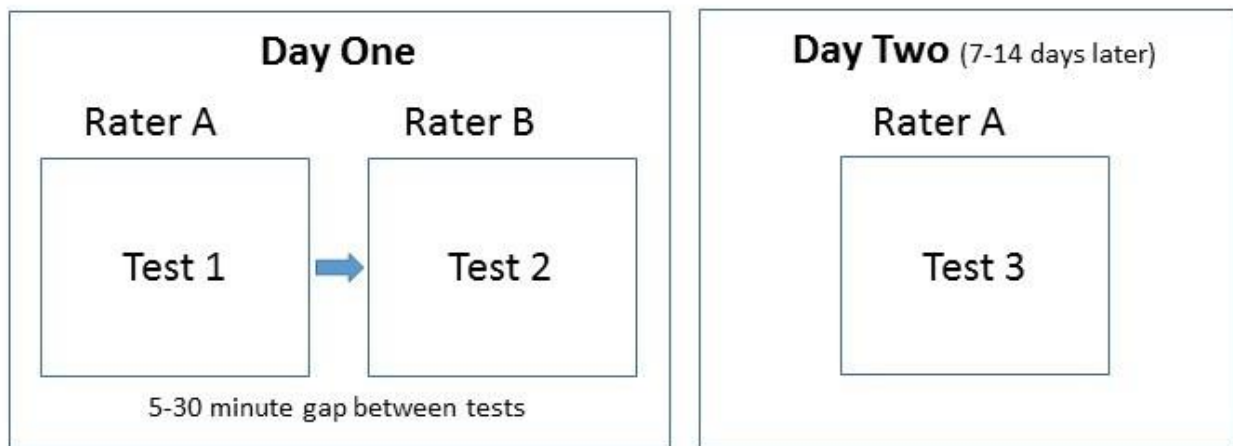
Figure 4.3 Flow diagram of assessment procedures

To standardise the testing procedures, 3 hours of practice for standardised palpation of bony landmarks, sensor placement and measurement procedures preceded the initial data collection. Standardised instructions were used by both raters with pre-determined verbal cues for each movement test. Rater order (i.e. who administered Tests 1 or 2) was randomised pragmatically by rater availability. Participants were tested in the same room for all tests, and where possible, were tested at a similar time of day. All kinematic data were automatically captured by the ViMove system independently of actions by the rater.

Equipment

The ViMove system (DorsaVi, Australia) is an inertial measurement system comprised of two wireless movement sensors containing a triaxial accelerometer, a triaxial gyroscope and a magnetometer, two wireless surface electromyography (EMG) sensors (these EMG data were not reported in this paper), and a small wireless recording device that can be easily carried (e.g. in a pocket). The manufacturer reports average differences of $< 1^{\circ}$ for single plane, through-range movements when comparing matched measurements from the ViMove and a Fastrak opto-electronic device (Charry, E et al., 2011). The ViMove movement sensors collect data at approximately 20 Hz.

Test procedures

Participants were partially undressed to expose the body from T12 to the posterior superior iliac spines (PSIS) (see Figure 4.1). Shoes were removed. The upper border of each PSIS was palpated and marked by Rater 1. To standardise sensor placement, the distance from the PSIS marker to the floor was recorded using a rigid vertical ruler and right-angled square. These measurements were used to replicate PSIS markings in subsequent testing (Kilby, J et al., 2012). A plastic template (part of the ViMove system) for standardising relative sensor placement was then aligned to the marking on the PSIS and used to guide sensor attachments. Movement sensors were attached to the skin over the T12 and S2 spinous processes using disposable adhesive pads. Movements were then demonstrated by the rater, after which participants were instructed to move through a standardised sequence of movements (summarised in Appendix L).

During these movements, data on lumbo-pelvic angles and ROM were recorded automatically by the device. The only role of the rater was to request the required movement in the required sequence and initiate the data collection process. On completion of a test, sensors and adhesive pads were removed and the skin was wiped clean. Participants rested for 5 minutes then the entire procedure was immediately repeated by a second rater. Each rater was blind to data collected by the other rater with the exception of the measurement of the vertical distance of the PSIS from the floor. Participants then returned 7-14 days later for a repeat assessment (Test 3) by Rater A. For participants with LBP, pain was recorded using three Numerical Rating Scales (worst pain =10, no pain =0), and the average of current, usual and worst pain over the previous 2 weeks was used (Chien CW, BK, Khan A, et al, 2013)). Activity limitation was assessed using the Roland Morris Disability Questionnaire (Roland, M et al., 2000). Pain and activity limitation were recorded on both assessment occasions.

Sample size

No existing data were available to inform sample size estimates. A sample of 60 adults aged 18-60 years (n=30 with LBP, n=30 without LBP) were recruited. This sample size would allow detection of a correlation of 0.44 or more between repeated measures in each group of 30, with an alpha of 0.05 and power of 0.8 (StataCorp., 2011). Arbitrarily, we assumed this was an adequate threshold, as movement consistency that resulted in lower retest correlations would provide adequate evidence that the individual variations in movement patterns would be so large that patterns of movements would be too variable to be clinically interpretable. In addition, a sample size of 30 is recommended where researchers are studying differences

between two sets of scores, as difference scores for samples of 30 or more are likely to assume a normal distribution and thereby provide more adequate data for parametric tests.

Data analysis

Data on body position were sampled and recorded at approximately 20Hz for each of the five repetitions of flexion, extension and left and right lateral flexion movements. Averaged lumbar lordosis angle was recorded in standing over a 5-second period.

Peak angles were calculated for trunk and pelvic sensors to indicate maximum angular displacement at T12 (trunk movement) and S2 (pelvic/hip movement). Lumbar movement (movement between T12 to S2) was calculated by subtracting pelvic movement (movement of the lower sensor at S2) from trunk movement (movement of the upper sensor at T12). In addition to static posture and ROM, data on 'lumbar versus pelvic' contribution to flexion, extension and lateral flexion were collected during each movement. This is shown graphically in Figure 4.4. A summary measure of this pattern of lumbar versus pelvic contribution to trunk movement (lumbo-pelvic rhythm) was estimated by calculating the percentage contribution of lumbar ROM to peak trunk ROM for flexion, extension and lateral flexion.
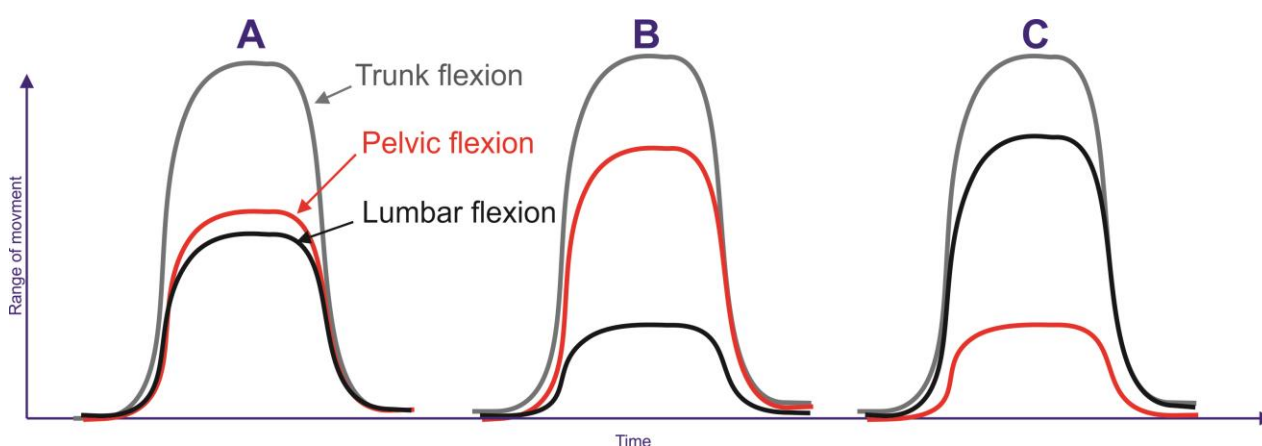
Figure 4.4 Examples of lumbo-pelvic rhythm movement patterns for flexion
Trunk flexion ROM = grey line, pelvic (hip) flexion, ROM = red line, and lumbar flexion ROM = black line. Peak trunk flexion angles, recorded with the T12 sensor, consist of two components: (1) pelvic (pelvis-on-hip) movement and (2) lumbar movement. (a) Typical flexion movement pattern of slightly greater pelvic compared to lumbar contribution to trunk movement. (b) Stiff lumbar spine with small lumbar contribution and mostly pelvic movement contributing to trunk flexion. (c) Greater lumbar and relatively smaller pelvic movement

Statistical analysis

Participant demographics (sex, BMI, pain and activity limitations) were summarised.

Comparing ROM for participants with and without LBP

Mean ROM scores for each of the repetitions (three tests each of five repetitions) for each movement, for LBP and NoLBP participants, were tested for differences between groups using a repeated measures ANOVA.

Consistency in repeated measurements

To examine the overall consistency in repeated movements, the standard deviation of all measurements of a movement for each participant was calculated. Differences in standard deviations between groups were tested using independent t-tests.

Within-test repeated movement consistency

Each of the three tests consisted of five repetitions for each movement. We considered that the best estimate of a person's ROM would most likely be an average of repeated measurements. Before commencing analysis of the magnitude of error in movement estimates, the five repetitions for Test 1 were examined to determine whether any of the repetitions were systematically different from others. Systematic variation for specific repetitions was assessed using a paired t-test to compare the mean for the first repetition to the mean for each of the other repetitions; this was repeated for repetitions 2, 3, 4 and 5, for each movement, and for LBP and NoLBP participants separately. Based on this analysis, we made decisions regarding the repetitions that were suitable for inclusion in subsequent analyses.

Movement consistency between tests on the same day (inter-rater reliability)

The average of stable repetitions was used as best evidence of the typical movement for each participant. Consistency between repeated tests was estimated using the two-way, random effects, absolute agreement between two raters, Intraclass Correlation Coefficient (ICC 2, 2) statistic. The magnitude of differences between repeated tests was summarised using Bland-Altman plots with 95% limits of agreement (LOA) and the minimal detectable change (MDC_{90}) statistic. These were calculated using the standard deviation of the differences between repeated tests multiplied by 1.65 for the MDC_{90} and 1.96 for 95% confidence levels (LOA). The MDC_{90} metric with its 90%CI balances statistical rigour with clinical utility in deciphering changes in measurements.

Movement consistency between tests on different days (7-14 days after the first test: intra-rater reliability)

Methods used to calculate the consistency of measurements taken on the same day were repeated for measurements taken on two test occasions 7-14 days apart. The conceptual framework and definitions of reliability used in this study were those published by the COSMIN group(Mokkink, LB et al., 2010). All analyses were performed using a statistical software package (STATA, version 12).

4.3.4. Results

Demographics

Participant sex, age, BMI, LBP intensity and activity limitation are presented in Table 4.1. There was a significant difference between groups in age. People with LBP were, on average, 10.3 years older than people without LBP.

Table 4.1 Participant demographics

	n	Gender (% female)	BMI (kg/m^2)	Age (years)	Pain (0-10 scale)	Activity limitation (RMDQ 24)
NoLBP group	32	42%	24.4 ± 3.1	35.5* ± 12.4	No pain	No activity limitation
LBP group (Test 1	30	50%	24.1 ± 5.6	45.8 ± 11.6	4.5 ±1.3	6.2 ± 3.5
LBP group (Test 3)					4.5 ±1.3	4.7 ± 2.6**

All numbers indicate mean ± standard deviation

* Significant difference in age between groups, p=.001

** Significant difference for activity limitation between Test 1 versus Test 3 in the LBP group

Comparing ROM for participants with and without LBP

Peak ROM scores for movement repetition are illustrated in Figure 4.5 and detailed in Table 2. Despite the typical differences in mean scores between LBP and NoLBP participants, these were significant only for pelvic ROM in flexion (LBP 60.8 $^{\circ}$, NoLBP 54.8°, $F_{(1,63)}$ =4.31, p = 0.04), lumbar ROM in right lateral flexion (LBP 22.2°, NoLBP 24.6° $F_{(1,63)}$ = 4.48, p = .04 and trunk ROM in right lateral flexion (LBP 28.4°, NoLBP 31.7°, $F_{(1,63)}$= 5.9, p = .02).
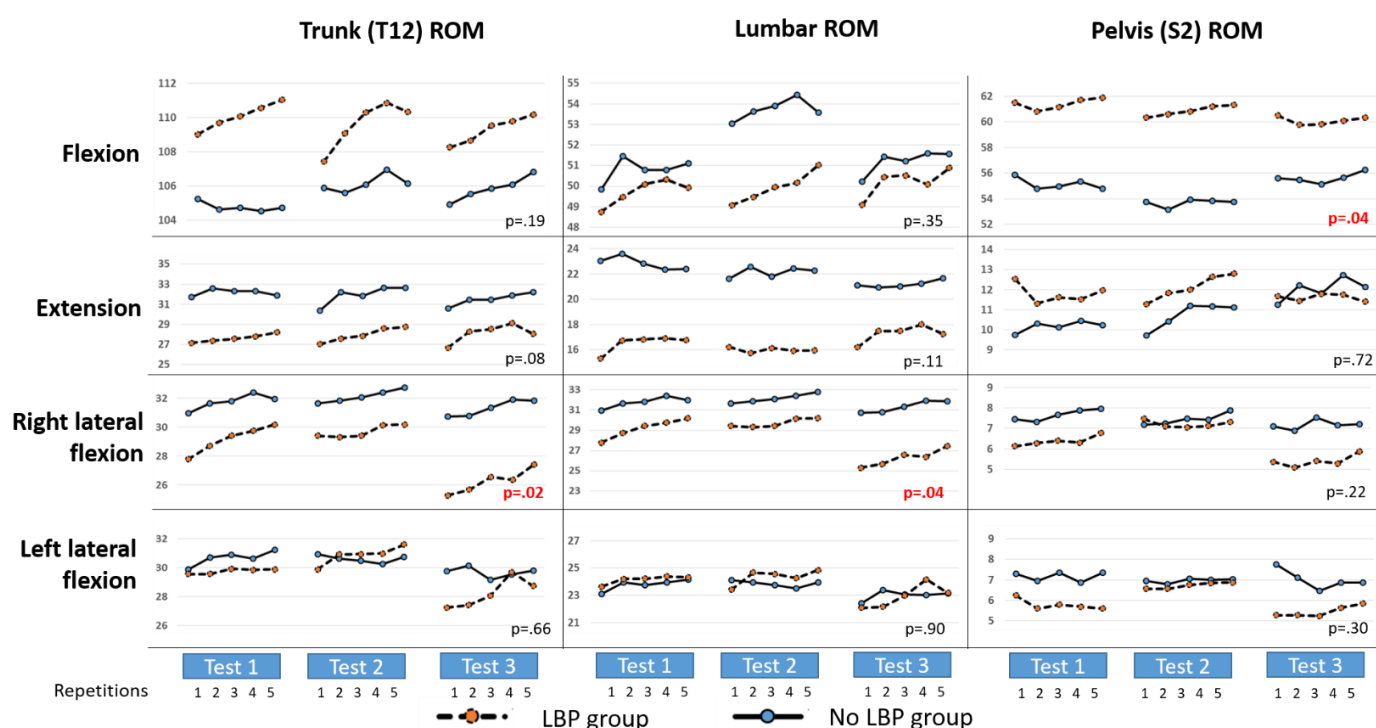
Figure 4.5 Repetition consistency
The total range (trunk ROM) and its components of lumbar ROM and pelvic ROM are presented for LBP and NoLBP participants for measurements taken on each of the three test occasions. P values reflect differences between NoLBP and LBP groups with significance set at > .05.

Consistency in repeated measurements

There were no significant differences between LBP and NoLBP participants in consistency of the 15 repetitions of each movement (5 repetitions x 3 tests) with the exception of trunk movement during right lateral flexion, where the standard deviation was significantly greater for the LBP group (2.7° ± .25°) compared to the NoLBP group (1.98° ± .14°).

Within-test repeated movement consistency

On examination of pairwise comparisons of repetitions 1 to 5, little evidence was found of significant effects attributable to repetition. Exceptions were lumbar flexion, and right lateral flexion (trunk and lumbar ROM) where (typically for both groups) ROM for the first repetition exhibited significantly smaller ROM than all other repetitions. Figure 4.5 shows similar patterns when other movements were considered. Consequently, repetition one was removed from subsequent analyses.

Movement consistency between tests

Lordosis and ROM

Table 4.2 summarises data for lordosis and ROM. Mean lordosis angles (across all three tests) for the two groups were not significantly different: $30.1^o \pm 11.1^o$ for the NoLBP group and $27.8^o \pm 11.2^o$ for the LBP group. The minimal detectable change based on the middle 90% of scores (MDC_{90}) for measurements of lordosis taken on the same day was $\pm 11.3^o$ for the NoLBP group and $\pm 8.8^o$ for the LBP group, and approximately $\pm 15^o$ (both groups) for different-day comparisons.

Different-day measurements generally showed greater inconsistency than measurements taken on the same day. For example, trunk flexion for the LBP group would have to change by more than $\pm 8.7^o$ (MDC_{90}) between tests on the same day for 90% confidence that observed changes were not due to typical variation in these measurements. This increases to $\pm 10.2^o$ change for tests on different days. An example of Bland Altman plots displaying the limits of agreement (95% confidence intervals), for flexion, can be seen in Figure 4.6. Trunk ROM measurement consistently showed greater stability compared to lumbar or pelvic ROM measurements for same-day and different-day comparisons. For example, for the LBP group, the MDC_{90} of trunk flexion for different-day tests was 10.2^o, compared to an MDC_{90} of 17° for lumbar ROM, and an MDC_{90} of 19° for pelvic ROM.

Intra-rater agreement using Bland-Altman plots for flexion

Inter-rater agreement using Bland-Altman plots for flexion

Range of motion

Legend: —— Mean rater ROM —— Upper and lower limits of agreement 95%CIs ○ NoLBP group ○ LBP group

Figure 4.6 Bland-Altman plots for trunk, lumbar and pelvic lumbar flexion

Lumbo-pelvic rhythm

Table 4.3 summarises the percentage contribution of lumbar ROM to trunk ROM (lumbo-pelvic rhythm). A significant difference between groups was seen for flexion (NoLBP 51.3% ± 9.4%, LBP 45.8% ± 8.6%, $F_{(1,63)}$ =4.20, p=.0445). MDC$_{90}$ scores for lumbo-pelvic rhythm suggest changes of relative lumbar versus pelvic contribution to trunk movement of between 9 and15% would, for 90% of tests, indicate true change for flexion and lateral flexion, while changes between 36 and 56% are required to be similarly sure of true change for extension (see Table 4.4).

Table 4.2 Lordosis and ROM scores, and consistency between tests (degrees)

Movement	Region	Back pain status	ROM*				Inter-rater agreement (same-day, different raters) Test 1 versus Test 2		Intra-rater agreement (different-days, same rater) Test 1 versus Test 3	
			Test 1	Test 2	Test 3	Average for all 3 Tests	Mean & SD of differences between Test 1 & Test 2**	Minimal detectable change score	Mean & SD of differences between Test 1 & Test 3**	Minimal detectable change score
Lordosis[†]	**Lumbar lordosis**	NoLBP	**-29.6 ± 11.2**	**-31.2 ± 11.3**	**-29.4 ± 10.8**	**-30.1±11.1**	**1.5 ± 6.9**	**± 11.3**	**-0.5 ± 9.1**	**± 15.0**
		LBP	**-27.1 ± 11.6**	**-28.1 ± 10.5**	**-28.2 ± 11.8**	**-27.8 ± 11.2**	**1.0 ± 5.4**	**± 8.8**	**0.2 ± 9.0**	**± 14.8**
	Trunk angle	NoLBP	-9.9 ± 5.7	-10.5 ± 5.1	-11.0 ± 4.2	-10.4 ± 5.0	0.6 ± 4.2	± 6.9	1.2 ± 4.7	± 7.7
		LBP	-9.5 ± 5.5	-9.4 ± 4.0	-9.9± 4.5	-9.6 ± 4.7	0.0 ± 3.7	± 6.1	0.3 ± 3.4	± 5.6
	Pelvic angle	NoLBP	19.7 ± 10.0	20.7 ± 9.6	18.4 ± 9.6	19.6 ± 9.7	-1.0 ± 5.5	± 9.0	1.7 ± 7.2	± 11.9
		LBP	17.6 ± 9.3	18.7 ± 10.8	18.4 ± 10.4	18.2 ±10.1	-1.1 ± 5.8	± 9.6	0.0 ± 7.9	± 13.0
Flexion[†]	**Trunk (T12) angle**	NoLBP	**104.9 ± 15.4**	**106.4 ± 15.5**	**105.8 ± 15.7**	**105.7 ± 15.4**	**-1.5 ± 4.1**	**± 6.8**	**-0.4 ± 5.7**	**± 9.3**
		LBP	**110.4 ± 14.3**	**110.2 ± 13.2**	**109.6 ± 13.1**	**110.1 ± 13.4**	**0.2 ± 5.3**	**± 8.7**	**-0.4 ± 6.2**	**± 10.2**
	Lumbar range	NoLBP	51.2 ± 8.1	54.1 ± 8.9	50.9 ± 10.1	52.1 ± 9.1	-2.9 ± 6.6	± 10.8	-0.4 ± 7.9	± 13.0
		LBP	49.9 ± 11.6	50.1 ± 11.4	50.5 ± 11.5	50.2 ± 11.3	-0.2 ± 5.0	± 8.4	-0.2 ± 8.4	± 14.0
	Pelvic (S2) angle	NoLBP	54.9 ± 15.3	53.7 ± 14.6	55.8 ± 15.5	54.8 ± 15.0‡	1.2 ± 5.0	± 8.2	0.2 ± 6.6	± 10.9
		LBP	61.0 ± 12.4	60.0 ± 14.4	61.2 ± 12.4	60.8 ± 13.2‡	0.4 ± 7.1	± 11.8	-1.0 ± 9.9	± 16.6
Extension[†]	**Trunk angle**	NoLBP	**32.3 ± 8.9**	**32.3 ± 9.5**	**31.7 ± 7.3**	**32.1 ± 8.6**	**0.0 ± 6.1**	**± 10**	**-0.6 ± 6.0**	**± 9.9**
		LBP	**27.1 ± 7.0**	**26.2 ± 7.6**	**27.4 ± 6.2**	**26.9 ± 7.0**	**-0.9 ± 3.9**	**± 6.3**	**1.0 ± 4.4**	**± 7.2**
	Lumbar range	NoLBP	22.8 ± 13.9	22.3 ± 12.2	21.2± 12.4	22.1 ± 12.8	-0.5 ± 7.6	± 12.5	-2.2 ± 11.3	± 18.6
		LBP	15.1 ± 8.5	15.2 ± 10.6	15.6 ± 7.2	15.2 ± 8.9	0.1 ± 5.5	± 9.0	1.4 ± 3.8	± 6.2
	Pelvic angle	NoLBP	11.3 ± 8.5	11.5 ± 8.2	12.7 ± 9.3	11.8 ± 8.6	0.2 ± 5.9	± 9.7	1.8 ± 8.4	± 13.8
		LBP	12.3 ± 8.4	11.3 ± 9.7	12.0 ± 7.8	11.9 ± 8.7	-1.1 ± 6.2	± 10.1	-0.3 ± 4.6	± 7.6
Left lateral flexion[†]	**Trunk angle**	NoLBP	**31.2 ± 6.6**	**30.7 ± 6.0**	**29.9 ± 5.4**	**-30.6 ± 6**	**-0.5 ± 4.1**	**± 6.9**	**-0.8 ± 4.9**	**± 8.1**
		LBP	**29.8 ± 6.0**	**31.1 ± 6.5**	**28.5 ± 6.1**	**-29.9 ± 6.2**	**1.3 ± 3.9**	**± 6.5**	**-0.7 ± 3.4**	**± 5.7**
	Lumbar range	NoLBP	24.1 ± 4.7	23.9 ± 4.3	23.3 ± 4.6	-23.8 ± 4.5	-0.2 ± 3.3	± 5.5	-0.2 ± 3.9	± 6.6
		LBP	24.3 ± 5.3	24.6 ± 5.9	23.1 ± 5.9	-24.1 ± 5.7	0.3 ± 3.5	± 5.8	-1.1 ± 3.2	± 5.3
	Pelvic angle	NoLBP	7.3 ± 4.1	7.1 ± 3.8	6.9 ± 3.6	-7.4 ± 3.8	-0.2 ± 2.5	± 4.2	-0.5 ± 2.7	± 4.5
		LBP	5.7 ± 2.8	6.8 ± 3.7	5.5 ± 3.5	-6.0 ± 3.4	1.1 ± 2.6	± 4.3	0.3 ± 2.4	± 4.1

Right lateral flexion†	**Trunk angle**	NoLBP	**31.9 ± 6.0**	**32.4 ± 6.5**	**31.6 ± 6.5**	**32 ± 6.2**	**-0.5 ± 2.9**	**± 4.9**	**-0.2 ± 2.7**	**± 4.5**
		LBP	**29.5 ± 5.1**	**29.8 ± 5.1**	**26.5 ± 5.7**	**28.8 ± 5.4**	**-0.3 ± 4.0**	**± 6.6**	**-2.6 ± 3.5**	**± 5.8**
	Lumbar range	NoLBP	24.4± 4.6	24.9 ± 4.5	24.7 ± 4.6	24.7 ± 4.5	-0.5 ± 2.4	± 4.0	-0.7 ± 3.1	± 5.2
		LBP	23.2 ± 5.2	22.8 ± 4.6	21.3 ± 5.7	22.3 ± 5.6	0.4 ± 3.0	± 5.1	1.9 ± 2.6	± 4.3
	Pelvic angle	NoLBP	7.7 ± 3.9	7.7 ± 4.0	7.1 ± 3.8	7.5 ± 3.9	0.0 ± 2.5	± 4.1	0.6 ± 2.7	± 4.5
		LBP	6.4 ± 2.9	7.1 ± 3.3	5.4 ± 3.3	6.4 ± 3.2	-0.7 ± 3.1	± 5.1	0.7 ± 2.8	± 4.8

Legend: LBP= LBP group, NoLBP= No LBP group, ROM= ROM

* ROM and standard deviation data represent the group mean and standard deviation (SD). The standard deviation indicates the magnitude of differences between individuals within the group

** These data are derived from the difference in ROM between tests for each individual, (i.e. Test 1 versus 2, Test 1 versus 3) then calculating group mean and SD of the difference scores.

† See table 4 for numbers (n) of participants in each group

‡ Indicates significant difference between groups

Table 4.3 Lumbo-pelvic rhythm (expressed as the percentage of lumbar contribution to trunk ROM) and consistency between tests

Movement	Back pain status	Average % Lumbar movement for each test*				Inter-rater agreement (same-day, different raters)		Intra-rater agreement (different-days, same rater)	
		Test 1	Test 2	Test 3	Average for all 3 Tests	Mean & standard deviation of differences ** between Test 1 vs Test 2	Minimal detectable change (MDC$_{90}$)	Mean & standard deviation of differences ** between Test 1 vs Test 3	Minimal detectable change (MDC$_{90}$)
Flexion†	**NoLBP**	51.9% ± 9.6%	50.0% ± 9.0%	52.0% ± 9.6%	**51.3% ± 9.4%**	1.9% ± 5.5%	9.1%	0.8% ± 7.0%	11.5%
	LBP	45.4% ± 8.9%	45.6% ± 8.6%	46.4%10.7%	**45.8% ± 8.6%**	0.2% ± 5.9%	8.5%	0.5% ± 9.4%	15.5%
Extension†	**NoLBP**	68.4% ± 34.0%	68.9% ± 31.2%	66.6% ± 33.2%	**68.0% ± 32.3%**	0.5% ± 22%	36.3%	2.6% ± 34.2%	56.2%
	LBP	58.2% ± 30.2%	56.2% ± 30.6%	59.0% ± 29.7%	**56.9% ± 33.7%**	2.0% ± 25.2%	41.4%	1.1% ± 31.8%	52.3%
Left lateral flexion†	**NoLBP**	78.5% ± 10.0%	78.7% ± 9.0%	79.0% ± 9.8%	**78.6% ± 9.5%**	0.2% ± 7.3%	12.0%	0.6% ± 7.2%	11.8%
	LBP	81.6% ± 8.2%	79.2% ± 10.2%	81.1% ± 10.4%	**80.6% ± 9.6%**	2.4% ± 7.3%	12.0%	1.6% ± 7.2%	11.8%
Right lateral flexion†	**NoLBP**	77.4% ± 9.5%	78.2% ± 8.8%	79.3% ± 8.3%	**78.0% ± 9.1%**	0.7% ± 6.8%	11.2%	2.3% ± 6.3%	10.4%
	LBP	78.4% ± 9.4%	76.6% ± 9.4%	80.2% ± 11.6%	**78.3% ± 10.0%**	1.8% ± 8.2%	13.5%	1.0% ± 8.9%	14.6%

* Calculated by dividing lumbar ROM over trunk ROM then converting to percentage
** See explanation in Table 3 footnote regarding methods used in calculating the SD of difference scores.
† See table 4 for numbers (n) of participants in each group

Inter-rater and intra-rater reliability

ICCs (Table 4.4) across all measured characteristics averaged r =.88 (range .80 to .98) for same-day inter-rater reliability and r =.85 (range .67 to .97) for different-day intra-rater reliability. All ICCs were below P=.005. The results for both intra and inter-rater agreement demonstrate good to excellent agreement for almost all comparisons (Portney, LG et al., 2009).

Table 4.4 Inter-rater and Intra-rater reliability (Intraclass Correlation Coefficients using mean of repetitions 2-5)

Interrater	NoLBP subjects				LBP subjects			
	n =	T12 angle	Pelvic angle	Lumbar ROM	n =	T12 angle	Pelvic angle	Lumbar ROM
Flexion	32	.98 (.96 to .99)	.97 (.94 to .99)	.80 (.56 to .91)	32	.96 (.92 to .98)	.92 (.84 to .96)	.95 (.90 to .98)
Extension	31	.88 (.74 to .94)	.87 (.72 to .93)	.91 (.81 to .96)	28	.95 (.90 to .98)	.77 (.52 to .89)	.94 (.87 to .97)
Lordosis	33	.83 (.65 to .91)	.91 (.83 to .96)	.90 (.79 to .95)	32	.83 (.65 to .92)	.91 (.81 to .96)	.94 (.87 to .97)
Lateral Flexion left	33	.88 (.76 to .94)	.89 (.77 to .94)	.84 (.68 to .92)	32	.89 (.76 to .94)	.79 (.56 to .90)	.89 (.78 to .95)
Lateral flexion right	33	.94 (.88 to .97)	.88 (.72 to .95)	.92 (.84 to .96)	32	.82 (.64 to .91)	.67 (.33 to .83)	.89 (.79 to .95)
Intrarater	**NoLBP subjects**				**LBP subjects**			
Flexion	28	.97 (.93 to .99)	.95 (.90 to .98)	.86 (.68 to .94)	25	.95 (.89 to .98)	.86 (.69 to .94)	.86 (.69 to .94)
Extension	28	.84 (.64 to .92)	.71 (.38 to .86)	.79 (.54 to .90)	21	.94 (.88 to .98)	.67 (.25 to .86)	.94 (.87 to .97)
Lordosis	30	.71 (.40 to .86)	.84 (.68 to .93)	.81 (.59 to .91)	25	.89 (.74 to .95)	.82 (.60 to .92)	.85 (.65 to .93)
Lateral Flexion left	30	.77 (.53 to .89)	.85 (.69 to .93)	.76 (.49 to .89)	25	.92 (.82 to .96)	.83 (.61 to .92)	.92 (.81 to .96)
Lateral flexion right	30	.95 (.90 to .98)	.88 (.75 to .94)	.89 (.77 to .95)	25	.85 (.46 to .94)	.70 (.34 to .87)	.92 (.68 to .97)

Legend: ROM= ROM Intraclass correlation co-efficients (ICC 2,2) and 95% confidence intervals

4.3.5. Discussion

Overview

In this study, we assessed people with and without LBP and determined the consistency in measurements of their standing lordosis, active movement range and lumbo-pelvic rhythm over two tests on the same day and a third test 7-14 days later. We found that the LBP and NoLBP participants had similar standing lordosis angles and ROM, with the exception of greater pelvic ROM in flexion (LBP group), and greater trunk and lumbar ROM in right lateral flexion (NoLBP group). Although the LBP group demonstrated similar trunk ROM during flexion, this appeared to have been achieved through relatively greater pelvis/hip contribution. In addition, we found no significant difference in movement consistency between the NoLBP and LBP groups. Lastly, we found good to excellent inter-rater (same day) and intra-rater (different days) reliability for most

movements, with MDC$_{90}$ estimates for expected variation between tests in the order of 5-15° and MDC$_{90}$ estimates for lumbar contribution to lumbo-pelvic rhythm in flexion and lateral flexion that ranged from 8 to 15%. In contrast, the MDC$_{90}$ estimates for lumbar contributions to extension showed an expected variability that was in the order of 36-56% and these findings may limit the clinical utility of monitoring changes in lumbar contribution to extension.

ROM and variability comparisons

A recent meta-analysis identified that, on average, people with chronic LBP have less lumbar ROM than people who do not have LBP (Laird, R et al., 2014). Our data did not demonstrate any significant difference between groups in lumbar ROM, although there was a trend towards there being more hip and less lumbar spine involved in achieving flexion ROM for people with LBP (Figure 4.5). In addition, we noted less lumbar extension in people with LBP although this also did not achieve significance. These observations warrant confirmation through studies of independent samples of people with and without LBP.

Clinical utility depends on how much change a clinician expects to see and knowledge of how much change is due to biological variation and measurement error. ROM data for all components (i.e. trunk, lumbar and pelvic ROM) of flexion and lateral flexion, and for extension (trunk ROM only) indicate sufficient stability to be potentially clinically useful with MDC$_{90's}$ of 5-15° (flexion), 4-8° (lateral flexion) and 6-10° (trunk extension) indicating high probability of true change. However, changes to lumbar and pelvic extension were associated with higher retest variations, with MDC$_{90's}$ of 10-14° (pelvic movements) and up to 19° (lumbar spine movements). These findings may limit the clinical utility of using changes in lumbar spine extension ROM to monitor progress.

Trunk angle measurements were generally associated with smaller retest variations than lumbar or pelvic angle measurements, which may inspire the argument that trunk ROM is the more sensitive and potentially valuable outcome measure. Our data indicate however that people with LBP appear to retain full flexion ROM by increasing pelvic/hip movement while limiting lumbar contribution.

Inter-rater (same day) differences between tests were generally smaller than intra-rater (different day) differences. This is a common finding in reliability studies and is likely to be due to a combination of factors that occur between measurement days, such as normal biological variations, minor variations to experimental conditions and possible environmental factors. We studied intra-rater different-day

measurements as this reflects common clinical practice, making the results relevant to clinical decision-making.

Within-test repeated movement consistency

The first repetition of flexion and right lateral flexion movements was significantly different to subsequent repetitions, with similar, non-statistically significant, patterns seen for other movements (see Figure 4). As a consequence, we used repetitions 2-5 for analysis of movement consistency. This renders the study results relevant to clinicians who allow clients to practice the test before commencing measurement. The first repetition of a test may be affected by apprehension, uncertainty about what is required, fear of pain, movement stiffness, and distraction or inattention, to name only some of the possible factors that might explain this aspect of our data.

Lordosis

Lumbar lordosis angles are of clinical interest in assessing spinal alignment and postural archetypes. A wide range of group mean lordosis angles, measured by skin surface techniques, have been reported. A recent review of nine studies reported mean lordosis angles ranging from 23° to 55° (Laird, R et al., 2014). Mean (±SD) standing lordosis, measured in this study, ranged from 27° to 31° ± 11°, without any significant differences between LBP and NoLBP groups. In our data, relatively large variability in standing lordosis angles was seen between tests on both the same day and on different days with MDC_{90} scores ranging from 9° to 11° for tests on the same day and up to 15° for tests on different days. This variability may be a test artifact related to precision in sensor placement or it may be true biological variability. We were very particular in attempting precise sensor repositioning in repeated tests and it is unlikely that greater accuracy in sensor placement would be expected in typical clinical practice.

Lumbo-pelvic rhythm

Various patterns of lumbo-pelvic movement have been described but few patterns have been measured or reported as outcomes. Clinicians are interested in identifying the contributions to trunk movement from hip movement and lumbar spine movement. It has been proposed that when extremes of lumbar or pelvic contribution to trunk flexion are corrected, associated pain can be reduced (O'Sullivan, P.B., 2005b; Sahrmann, S, 2002b). This study showed relatively greater hip compared to lumbar contribution for the LBP group. We speculate that this maybe a compensatory mechanism as a response to reduced lumbar ROM. A recent meta-analysis (six studies) of typical lumbo-pelvic rhythm showed similar but non-significant findings

of reduced lumbar contribution to trunk flexion (Laird, R et al., 2014). Although lumbo-pelvic rhythm has been reported using a lumbar/pelvic angle ratio, we consider that percentage lumbar contributions to trunk movement are easier to visualise and circumvent the complexities associated with interpretation of ratios (that can be affected by both the numerator and the denominator). If trunk movement occurs entirely at the lumbar spine, the lumbo-pelvic rhythm will be 100%, while a person who bends with the pelvis/hips and without lumbar spine movement will score 0%.

In our data (Table 4.3), mean lumbar contribution to trunk flexion ranged from 46% ± 9% to 51% ± 9%. This is closely consistent with Kim et al (2013) who reported similar mean lumbar contributions to trunk flexion of 45%± 9% to 49% ± 9%.

Considerable test-to-test variability in the percentage contribution of pelvic and lumbar movement to trunk flexion was seen in our data for a small number of participants. An example of this variable motor control of lumbar and pelvic movement contribution, while maintaining relatively consistent trunk ROM, is shown in Figure 4.7. This NoLBP participant demonstrated an increase in lumbar contribution to trunk flexion from an initial 38% to 74%, despite little difference in overall trunk ROM of around 80°.
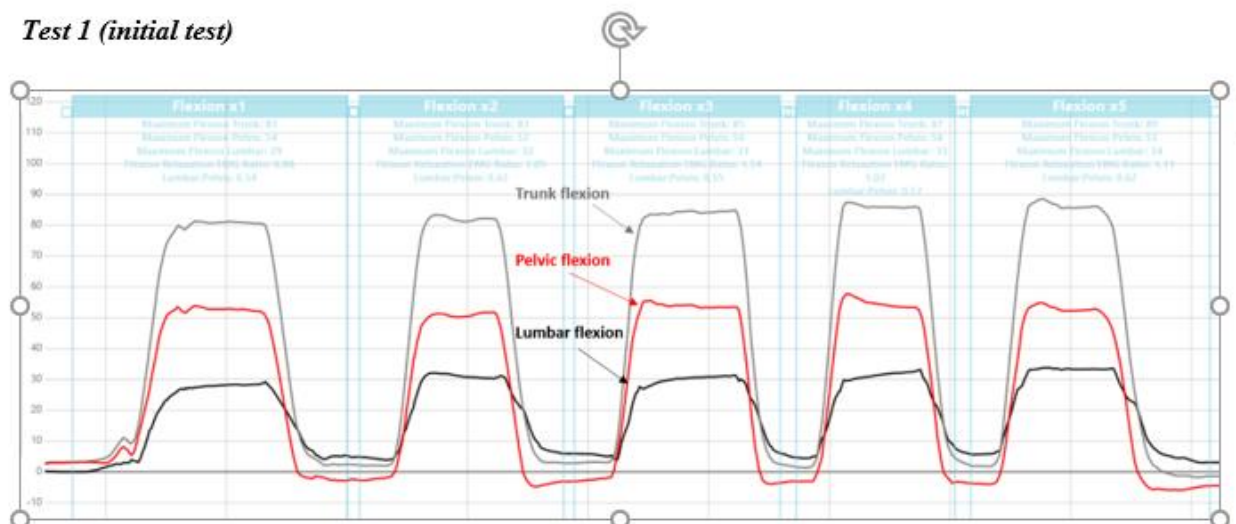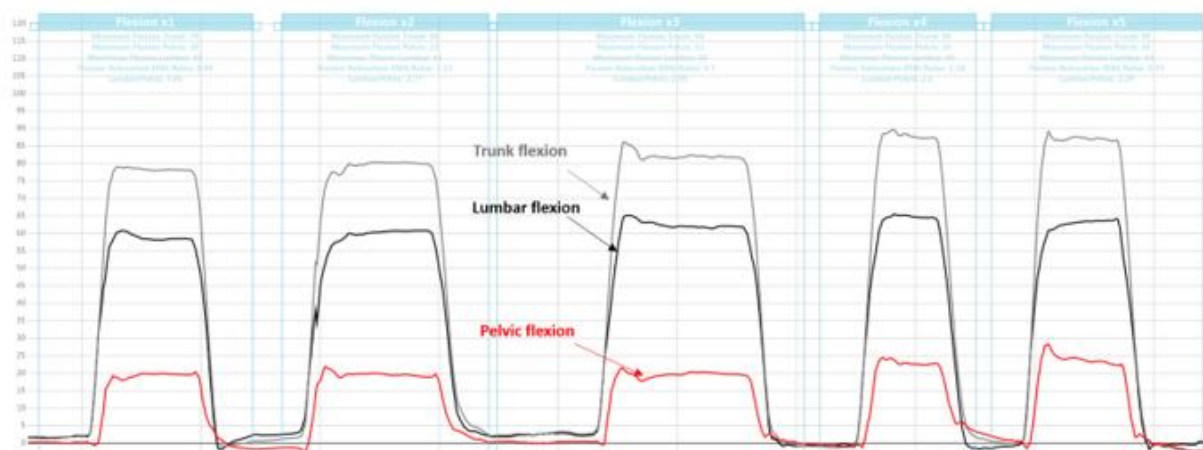
Figure 4.7 Flexion lumbo-pelvic rhythm differences on Test 1 versus Test 3

Tests taken two weeks apart) for participant No. 71 (NoLBP), illustrating large differences in movement between days for flexion and lumbo-pelvic rhythm in one participant. Grey line = trunk flexion, black line = lumbar flexion and the red line = pelvic (hip) flexion

Limitations of this study

Using a skin surface measurement technique to measure movement has the advantage of being non-invasive and possible within a typical clinical setting. However, any skin surface measurement technique has to be vigilant for artefacts that can occur due to issues such as skin buckling, sensor placement error, loss of sensor adherence to skin, etc. Excessive adipose tissue and skin buckling can alter the orientation of the surface-mounted movement sensor in some people, although simple observation can screen for this type of error. Skin surface measurement also has the inherent issue of sensor placement error, with relatively poor

reliability of manual palpation of bony landmarks (Kilby, J et al., 2012). However we attempted to reduce this error by additional linear measurement to reduce placement error for subsequent tests.

There is a significant difference between LBP and NoLBP groups for age, with the LBP group being older on average. Other studies have shown that ROM diminishes with age but these changes are more visible in the 5th and 6th decades (Intolo, P et al., 2009). While it is possible that age-related differences between groups may account for reduced movement in the LBP group (trunk and lumbar right lateral flexion), it is unlikely age would explain increased ROM (pelvic flexion) or the altered lumbo-pelvic rhythm (where trunk ROM was the similar for both groups). A significant difference for activity limitation was seen between Test 1 versus Test 3 for the LBP group but the difference between scores was 1.5 on the RMDQ and is unlikely to be clinically meaningful.

Rotational measurements were not technically possible with motion sensors at the time of testing but advances now allow for testing axial rotation. Further research should include rotation.

This study was not powered to test for differences between subgroups within the LBP population (pain intensity, presence of leg pain, mechanism of injury, movement pattern, aggravating activities etc.) so it possible that various subgroup definitions may demonstrate different results.

We conducted multiple ANOVAs when studying the differences in ROM for those with and without LBP, and retained our alpha level at .05 for all comparisons. Some observed differences between groups may therefore be chance findings, and the study findings warrant testing in independent studies.

A further limitation may be the single intra-rater comparison. Further studies could include multiple intra-rater comparisons to increase the robustness of extrapolating these results to other clinicians.

4.3.6.   Conclusion

This study compared the consistency of lumbar lordosis, lumbo-pelvic range of movement (ROM) and lumbo-pelvic rhythm in people with and without low back pain, over three test sessions: two tests on the same day and a third test, one to two weeks later. There was little difference between the LBP and NoLBP groups for lordosis angle, and most ROM conditions, with the exception of greater pelvic flexion, and reduced trunk and lumbar right lateral flexion ROM. Significantly reduced relative lumbar contribution to flexion lumbo-pelvic rhythm was seen in the LBP group. Movement consistency between each test was described by using MDC_{90} to measure between-test differences. Mean lumbar lordosis angles of approximately 30° required around 10°

change to have 90% confidence of seeing true change between same-day tests and 15° for different-day tests. ROM tests showed relatively greater consistency with changes ranging from 5 to15^o between tests required to similarly identify true change. Lumbo-pelvic rhythm changes of > 8-15% lumbar contribution to flexion and lateral flexion trunk ROM indicated probable change, while a larger change of >36-56% would be needed to be confident of change to an extension lumbo-pelvic rhythm.

Declarations

Abbreviations

LBP = Low Back Pain
NoLBP = participants without low back pain
RMDQ = Roland Morris Disability Questionnaire
ROM = Range of movement

Ethics approval and consent to participate

Ethics approval was obtained from Monash University Human Research Ethics Committee (approval number CF12/1995-20 12001090). All participants gave written informed consent for testing and use of de-identified data, through the use of an ethics committee approved patient information and consent form.

Consent for publication

Not applicable

Availability of data and materials

All raw data and information related to additional files can be obtained from the first author at robert.laird@monash.edu. All patient data has been de-identified.

Funding

No funding was received for this study.

Competing interests

No benefits in any form have been, or will be, received for this study from a commercial party related directly or indirectly to the subject of this paper. This paper does not contain information about drugs. The authors do not hold stocks or shares in any company that might be directly or indirectly affected by this study. No

patents have been applied for or received due to the content of this paper and there are no non-financial competing interests associated with this paper.

Authors' contributions

RL contributed to data collection. RL was the main author of this paper, with concept, writing, data analysis, interpretation, draft revision and gave approval of the final manuscript. JK provided concept guidance, statistical direction, analysis, draft revision and gave approval of the final manuscript. PK provided concept guidance, statistical analysis, draft revision and gave approval of the final manuscript. RL, JK and PK agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

4.3.7.   Bibliography for Laird et al (2016)

Bauer, C. M., Baumgartner, L., Schelldorfer, S., Ernst, M., & Lawrence, M. (2012). Technical validation of a new movement therapy system for treatment of low back pain. *Gait & Posture, 36*, S40.

Brumagne, S., Cordo, P., Lysens, R., Verschueren, S., & Swinnen, S. (2000). The role of paraspinal muscle spindles in lumbosacral position sense in individuals with and without low back pain. *Spine, 25*(8), 989-994.

Charry, E., Umer, M., & Taylor, S. (2011). Design and validation of an ambulatory inertial system for 3-D measurements of low back movements. *Proceedings of Seventh International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP 2011) IEEE Conference Publications (http://ieeexplore.ieee.org/document/6146618/)*.

Chien CW, B. K., Khan A, et al. (2013). Comparative responsiveness of verbal and numerical rating scales to measure pain intensity in patients with chronic pain. *Journal of Pain, 14*, 1653-1662.

Descarreaux, M., Blouin, J.-S., & Teasdale, N. (2005). Repositioning accuracy and movement parameters in low back pain subjects and healthy control subjects. *European Spine Journal, 14*(2), 185-191.

Esola, M. A., McClure, P. W., Fitzgerald, G. K., & Siegler, S. (1996). Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain. *Spine, 21*(1), 71-78.

Ha, T. H., Saber-Sheikh, K., Moore, A. P., & Jones, M. P. (2013). Measurement of lumbar spine range of movement and coupled motion using inertial sensors - A protocol validity study. *Manual Therapy, 18*(1), 87-91.

Hodges, P. W., Coppieters, M. W., MacDonald, D., & Cholewicki, J. (2013). New insight into motor adaptation to pain revealed by a combination of modelling and empirical approaches. *European Journal of Pain, 17*(8), 1138-1146.

Ikeda, K., & McGill, S. (2012). Can altering motions, postures, and loads provide immediate low back pain relief: A study of 4 cases investigating spine load, posture, and stability. *Spine, 37*(23), E1469-1475.

Intolo, P., Milosavljevic, S., Baxter, D. G., Carman, A. B., Pal, P., Munn, J., et al. (2009). The effect of age on lumbar range of motion: a systematic review. *Manual Therapy, 14*(6), 596-604.

Kent, P., Laird, R., & Haines, T. (2015). The effect of changing movement and posture using motion-sensor biofeedback, versus guidelines-based care, on the clinical outcomes of people with sub-acute or chronic low back pain-a multicentre, cluster-randomised, placebo-controlled, pilot trial *BMC Musculoskeletal Disorders, 16*, 131-150.

Kilby, J., Heneghan, N. R., & Maybury, M. (2012). Manual palpation of lumbo-pelvic landmarks: A validity study. *Manual Therapy, 17*(3), 259-262.

Kim, M., Kwon, O., Cynn, H., Kim, Y., et al. (2013). Comparison of lumbopelvic rhythm and flexion-relaxation response between 2 different low back pain subtypes. *Spine, 38*(15), 1260-1267.

Laird, R., Gilbert, J., Kent, P., & Keating, J. (2014). Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis. *BMC Musculoskeletal Disorders, 15*(1), 229.

Laird, R., Kent, P., & Keating, J. (2012). Modifying patterns of movement in people with low back pain - does it help? A systematic review. *BMC Musculoskeletal Disorders, 13*, 169.

Lariviere, C., Gagnon, D., & Loisel, P. (2000). The effect of load on the coordination of the trunk for subjects with and without chronic low back pain during flexion-extension and lateral bending tasks. *Clinical Biomechanics, 15*(6), 407-416.

Lee, R. Y. W., & Wong, T. K. T. (2002). Relationship between the movements of the lumbar spine and hip. *Human Movement Science, 21*(4), 481-494.

Long, A., Donelson, R., & Fung, T. (2004). Does it matter which exercise? A randomized control trial of exercise for low back pain. *Spine, 29*(23), 2593-2602.

Manniche, C., Asmussen, K., Lauritsen, B., Vinterberg, H., Kreiner, S., & Jordan, A. (1994). Low Back Pain Rating scale: validation of a tool for assessment of low back pain. *Pain, 57*(3), 317-326.

McClure, P. W., Esola, M., Schreier, R., & Siegler, S. (1997). Kinematic analysis of lumbar and hip motion while rising from a forward, flexed position in patients with and without a history of low back pain. *Spine, 22*(5), 552-558.

Mokkink, L. B., Terwee, C. B., Patrick, D. L., Alonso, J., Stratford, P. W., Knol, D. L., et al. (2010). The COSMIN study reached international consensus on taxonomy, terminology, and definitions of measurement properties for health-related patient-reported outcomes. *Journal of Clinical Epidemiology, 63*(7), 737-745.

Neblett, R., Mayer, T. G., Brede, E., & Gatchel, R. J. (2010). Correcting abnormal flexion-relaxation in chronic lumbar pain: responsiveness to a new biofeedback training protocol. *Clinical Journal of Pain, 26*(5), 403-409.

O'Sullivan, K. J., O'Sullivan, L., Campbell, A., O'Sullivan, P., & Dankaerts, W. (2012). Towards monitoring lumbo-pelvic posture in real-life situations: Concurrent validity of a novel posture monitor and a traditional laboratory-ased motion analysis system. *Manual Therapy, 17*, 77-83.

O'Sullivan, P. (2005). Diagnosis and classification of chronic low back pain disorders: maladaptive movement and motor control impairments as underlying mechanism. *Manual Therapy, 10*(4), 242-255.

Paquet, N., Malouin, F., & Richards, C. (1994). Hip-spine movement interaction and muscle activation patterns during sagittal trunk movements in low back pain patients. *Spine, 15*(5), 596-603.

Pincus, T., Kent, P., Bronfort, G., Loisel, P., Pransky, G., & Hartvigsen, J. (2013). Twenty-five years with the biopsychosocial model of low back pain – is it time to celebrate? A report from the Odense Forum XII. *Spine, 38*(24), 2118-2123.

Porter, J. L., & Wilkinson, A. (1997). Lumbar-hip flexion motion. A comparative study between asymptomatic and chronic low back pain in 18- to 36-year-old men. *Spine, 22*(13), 1508-1513; discussion 1513-1504.

Portney, L. G., & Watkins, M. P. (2009). *Foundations of clinical research: applications to practice* (3rd ed.). New Jersey: Pearson Prentice Hall.

Pynt, J., Mackey, M. G., & Higgs, J. (2008). Kyphosed seated postures: Extending concepts of postural health beyond the office. *Journal of Occupational Rehabilitation, 18*(1), 35-45.

Ribeiro, D. C., Sole, G., Abbott, J. H., & Milosavljevic, S. (2011). Cumulative postural exposure measured by a novel device: a preliminary study. *Ergonomics, 54*(9), 858-865.

Roland, M., & Fairbank, J. (2000). The Roland-Morris Disability Questionnaire and the Oswestry Disability Questionnaire. *Spine, 25*(24), 3115-3124.

Sahrmann, S. (2002). Diagnosis and treatment of movement impairment syndromes.

StataCorp. (2011). Stata Statistical Software: Release 12. College Station, TX: StataCorp LP.

Tafazzol, A., Arjmand, N., Shirazi-Adl, A., & Parnianpour, M. (2014). Lumbopelvic rhythm during forward and backward sagittal trunk rotations: Combined in vivo measurement with inertial tracking device and biomechanical modeling. *Clinical Biomechanics, 29*, 7+.

Van Dillen, L. R., Sahrmann, S. A., Norton, B. J., Caldwell, C. A., McDonnell, M. K., Bloom, N., et al. (2003). The effect of modifying patient-preferred spinal movement and alignment during symptom testing in patients with low back pain: a preliminary report. *Archives of Physical Medicine & Rehabilitation, 84*(3), 313-322.

Vos, T., Flaxman, A. D., Naghavi, M., Lozano, R., Michaud, C., Ezzati, M., et al. (2012). Years lived with disability (YLDs) for 1160 sequelae of 289 diseases and injuries 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *The Lancet, 380*(9859), 2163-2196.

4.4.   Summary and application of results

This study concluded that some ROM parameters and lumbo-pelvic rhythm had sufficient stability to be potentially useful in clinical practice with minimal detectable change scores (90% confidence) of 5° to 10° for trunk flexion, 4° to 7° for lateral flexion, 6° to 10° for trunk extension, and 9% to 15% (of lumbar contribution) for flexion lumbo-pelvic rhythm. Changes in measurements greater than these values would indicate a high probability of true change when comparing repeated measurements for an individual. The relative contribution of lumbar and pelvic ROM, particularly to flexion, demonstrated greater relative variability than trunk flexion. There was a large variability in lordosis measurements seen between measurements taken by different testers and on different days, suggesting that lordosis may not be a useful parameter on which to base judgements about clinical outcomes.

4.4.1.   Stability of lumbo-pelvic ROM kinematics during <u>within-session</u> testing

Typical physiotherapy support of an individual with LBP involves testing movement-related parameters, applying an intervention, then retesting, and looking for change both within and between sessions, usually with the same treating clinician. This approach guides clinical decisions about which intervention method to use and is an approach recommended by a number of key developers of therapeutic approaches for musculoskeletal pain (Maitland, G, 1986; McKenzie, R et al., 2003a; Mulligan, BR, 2004; Sahrmann S., 2002). Hahne et al. (2004) demonstrated that within-session improvements to ROM and pain that exceeded a pre-determined minimum score indicated a greater likelihood of improvements to pain between treatment sessions. This supports the notion that measuring within-session change may have clinical utility.

The data from Laird et al. (Laird, R et al., 2016) indicate that ***within-session*** ROM scores are sufficiently stable to be used to monitor change within a treatment session. In this study, within-session data were used to determine stability over five sequential repetitions, resulting in a decision to drop the first repetition, as it was consistently significantly different to the other four repetitions. These data can also be used to calculate the minimal detectable change scores for 90% confidence (MDC_{90}) for within-session change by determining the differences between the minimum and maximum scores of the remaining four repetitions for each individual. The means and standard deviations of variability scores for the 64 participants can be used to calculate the MDC_{90} by multiplying the standard deviation by 1.645. Based on these data, true within-session change (e.g.

comparing before and after treatment), could be concluded with even small changes in ROM. For example, changes of more than 5° for trunk flexion or more than 4° for trunk extension would represent a 90% probability of real change. Similar small changes are required when observing lumbo-pelvic rhythm. Lumbar lordosis angle data were reported over a 10-second period but were not repeated within the same session, so no data were available on the stability of repeated within-session measures of lordosis angles. Table 4.5 and Appendix M report data on within-session changes in greater detail. Such small changes in ROM would be difficult to recognise with visual observation alone, suggesting that motion sensors could play a role in identifying small systematic changes in movements. No differences were observed in within-session consistency between people with and without LBP for ROM or lumbo-pelvic rhythm.

Table 4.5 Within-session variation and minimal detectable scores (for 90% confidence)

Movement	Region	Back pain status	Parameter Mean (SD)	Within-session variability (range between minimum and maximum scores between repetitions 2-5) Average difference between min and max score over repetitions 2-5 for each individual	Minimal detectable change score
Flexion ROM	**Trunk (T12) angle**	NoLBP	**105.7 ± 15.4°**	**4.9 ± 2.6°**	**± 4.3°**
		LBP	**110.1 ± 13.4°**	**4.6 ± 2.9°**	**± 4.8°**
	Lumbar range	NoLBP	52.1 ± 9.1°	3.5 ± 2.1°	± 3.5°
		LBP	50.2 ± 11.3°	3.4 ± 2.6°	± 4.3°
	Pelvic (S2) angle	NoLBP	54.8 ± 15.0°	3.5 ± 2.1°	± 3.5°
		LBP	60.8 ± 13.2°	3.6 ± 1.9°	± 3.1°
Extension ROM	**Trunk angle**	NoLBP	**32.1 ± 8.6°**	**3.1 ± 2.2°**	**± 3.6°**
		LBP	**26.9 ± 7.0°**	**3.9 ± 2.1°**	**± 3.5°**
	Lumbar range	NoLBP	22.1 ± 12.8°	3.1 ± 2.2°	± 3.6°
		LBP	15.2 ± 8.9°	3.5 ± 2.3°	± 3.8°
	Pelvic angle	NoLBP	11.8 ± 8.6°	2.6 ± 1.7°	± 2.8°
		LBP	11.9 ± 8.7°	3.0 ± 2.0°	± 3.3°
Left lateral flexion ROM	**Trunk angle**	NoLBP	**-30.6 ± 6°**	**3.4 ± 2.3°**	**± 3.8°**
		LBP	**-29.9 ± 6.2°**	**3.3 ± 2.1°**	**± 3.5°**
	Lumbar range	NoLBP	-23.8 ± 4.5°	2.7 ± 1.8°	± 3.0°
		LBP	-24.1 ± 5.7°	2.6 ± 1.8°	± 3.0°
	Pelvic angle	NoLBP	-7.4 ± 3.8°	2.1 ± 1.7°	± 2.8°
		LBP	-6.0 ± 3.4°	1.5 ± 1.2°	± 2.0°
Right lateral flexion ROM	**Trunk angle**	NoLBP	**32.0 ± 6.2°**	**2.9 ± 1.6°**	**± 2.6°**
		LBP	**28.8 ± 5.4°**	**3.1 ± 1.7°**	**± 2.8°**
	Lumbar range	NoLBP	24.7 ± 4.5°	2.2 ± 1.4°	± 2.3°
		LBP	22.3 ± 5.6°	2.3 ± 1.4°	± 2.3°
	Pelvic angle	NoLBP	7.5 ± 3.9°	1.9 ± 1.3°	± 2.1°
		LBP	6.4 ± 3.2°	1.9 ± 1.7°	± 2.8°
Lumbo-pelvic rhythm		NoLBP	**51.3 % ± 9.4 %**	**3.6 % ± 2.2 %**	**± 3.6%**
		LBP	**45.8 % ± 8.6 %**	**3.3 % ± 2.0 %**	**± 3.3%**

4.4.2. Stability of lumbo-pelvic kinematics during between-session and between-day testing

Larger ROM changes are required to confidently identify changes in lumbo-pelvic kinematic parameters for *between-session* (same day, different tester) and *between-day* (different day, same tester) measurements. For example, the MDC$_{90}$ for trunk flexion in the LBP groups for within-session change was 5° compared to 9°

and 10° for between-session (same day) and between-days comparisons respectively. The larger MDC$_{90}$ scores are most likely explained by additional sources of error from small differences in placement of sensors, differing instructions from testers (although attempts to minimise this type of error were undertaken by using a standardised method and by training the testers), and normal biological variations. For example, people may reduce ROM due to increasing pain, fatigue or boredom, while others may increase their ROM due to reducing pain, stretching of tighter tissues or relaxing muscles. There may be additional changes to a persons' wellbeing between days that could also account for larger between-day difference scores. It is also possible that the observed differences are attributable to genuine differences in the way that people move from one day to the next, as the factors that might affect overall mobility are not well understood. Between-day MDC$_{90}$ scores for most parameters, such as all directions of trunk angular inclination at T12 (flexion 10°, extension 7°, lateral flexions 6°), may be useful for monitoring change in situations where interventions are expected to cause changes in target parameters of this magnitude or more.

4.4.3.   Between-group differences

This study concluded that there were few differences in mean ROM between the LBP and NoLBP groups. This contradicted expectations based on results from Laird et al. (2014) that lumbar ROM might be smaller for the persistent LBP group. (Explanations for the differing results are offered in section 5.8).

Although the identification of between-group measurement differences were not the main aim of this study, they do provide useful, preliminary mean values for lordosis, ROM and lumbo-pelvic rhythm using this specific type of measurement tool. The data are comparable to studies that have used opto-electronic or inertial motion sensor devices to measure lordosis (Nourbakhsh, MR et al., 2001; Waddell, G et al., 1992), ROM (Bauer, CM et al., 2015; Ha, TH et al., 2013; Kim, M et al., 2013; Tsai, Y et al., 2010) and lumbo-pelvic rhythm (Kim, M et al., 2013), suggesting that measurements obtained using this device reflect data obtained in other studies. Table 4.6 displays the comparative ROM scores from other studies and those reported by Laird et al. (2016) in this chapter. These data are encouraging in that measurements across studies appear to be clustering around a relatively consistent range, providing optimism about the potential for normative data to guide assessments in the future.

Table 4.6 Comparison of group means for similar measurement devices

	Measurement Device		Number of subjects	Age (years ± SD)	Trunk ROM* (T12 angular inclination unless stated otherwise)	Lumbar ROM	Pelvic ROM (S1 angular inclination)
Laird et al. 2016 (Laird, R et al., 2016)	Inertial motion sensors (ViMove)	NoLBP	32	36 ± 12	106 ±15°	52 ± 9°	55 ±15°
		LBP	30	46 ± 11	110 ±13°	50 ±11°	61 ±13°
Kim et al. 2013 (Kim, MH et al., 2013)	Opto-electronic (Vicon)	NoLBP	16	24 ± 3	-	49 ± 7°	57 ±10°
		LBP	31	24 ± 3	-	52 ± 8°	53 ± 9°
Bauer et al. (Bauer, CM et al., 2015)	Opto-electronic (Vicon)	NoLBP	22	41 ± 11	-	51 ± 10°	77 ± 14°
	Inertial motion sensors (Valedo)		22	41 ± 11	-	53 ± 11°	77 ± 15°
Tsai et al. 2010 (Tsai, Y et al., 2010)	Opto-electronic (Vicon)	NoLBP	16	48 ± 8	-	55 ± 11°	-
		LBP	16	49 ± 7	-	56 ±12°	-
Ha et al. (Ha, TH et al., 2013)	Electromagnetic (Fastrack)	No LBP	26	28 ± 7	-	57°	-
	Inertial motion sensors (XSens)		26	28 ± 7	-	57°	-
Shahparvour et al. (Shahvarpour, A et al., 2017)	Inertial motion sensors (XSens)	NoLBP and LBP combined	60	42 ± 14	115 ± 14°	50 ± 9°	63 ±13°

Trunk angle recorded at any level i.e. T1, T7, T12 etc. would be acceptable

4.4.4. Measurement tool appraisal

Data from motion and EMG sensors add increased detail, and improve visual observations by quantifying speed, regional timing, movement patterns, postural angles and activation of lumbar extensor muscle activity. There is additional clinical utility with software processes that collect and interpret data automatically, providing numerical and graphical interpretation of movement that enable comparisons of within-session and between- session data. Data from motion sensors are likely to have greater accuracy than estimates obtained by visual observation, although this is yet to be demonstrated. Motion sensor data also have significant potential as a therapeutic tool through the use of real-time biofeedback for clinicians and patients (Kent, P et al., 2015a).

4.4.5.   Is motion sensor technology valid and accurate?

The concurrent validity of data from inertial motion sensor technology has been investigated by comparison with opto-electronic laboratory-based measurements of lumbo-pelvic movement. Concurrent validity studies of other devices are often compared with measurements derived from a Vicon opto-electronic system. The Vicon opto-electronic system is often referred to as the 'gold standard' of laboratory-based measurement systems (Beckwee, D et al., 2016; Godwin, A et al., 2009; Gray, AD et al., 2017; Muller, B et al., 2017) with a spatial accuracy of less than 2mm (Merriaux, P et al., 2017). Mjosund et al. (2017) compared Vimove motion sensors with Vicon opto-electronic data in 18 people with LBP and 16 people without LBP, comparing 'through-range' ROM (see Figure 4.8). They reported root mean squared errors of less than 2°, mean differences of less than 0.5^o and 95% limits of agreement at -3.9^o to 4.7^o, suggesting clinically acceptable agreement between the two measurement devices. Similar findings of concurrent validity of Vimove to opto-electronic measurements are reported by Charry et al. (2011). Bauer et al. (2012) compared the Valedo inertial motion sensor system with Vicon, and Wong et al. (2008) compared an inertial-based posture monitoring system with Vicon, both studies reporting high levels of concurrent validity. Godwin et al. (2009) compared the accuracy of inertial motion sensors (the XSens system) with the Vicon system in static, quasi-static and complex dynamic motions. They found mean differences of less than 1° error in static and quasi-static for single axis movement with root mean square errors between 1.9-3.5^o on the main axis of motion. Charry et al. reported the accuracy of the Vimove device as 1° (95%CI ± 1.8^o) in the sagittal plane and 2° (95%CI ± 3.6^o) in the frontal plane. This accuracy and concurrent validity indicate that Vimove and other motion sensors provide data that have sufficiently small error to be clinically useful. The error of the tool itself (independent of human variability) is lower than the measurement error reported in this chapter (which includes biological variability), suggesting that the device itself is highly accurate.

Figure 4.8 A comparison of concurrent Vimove and Vicon data during lumbar flexion

(image reproduced with permission from Mjosund et al. (2017)
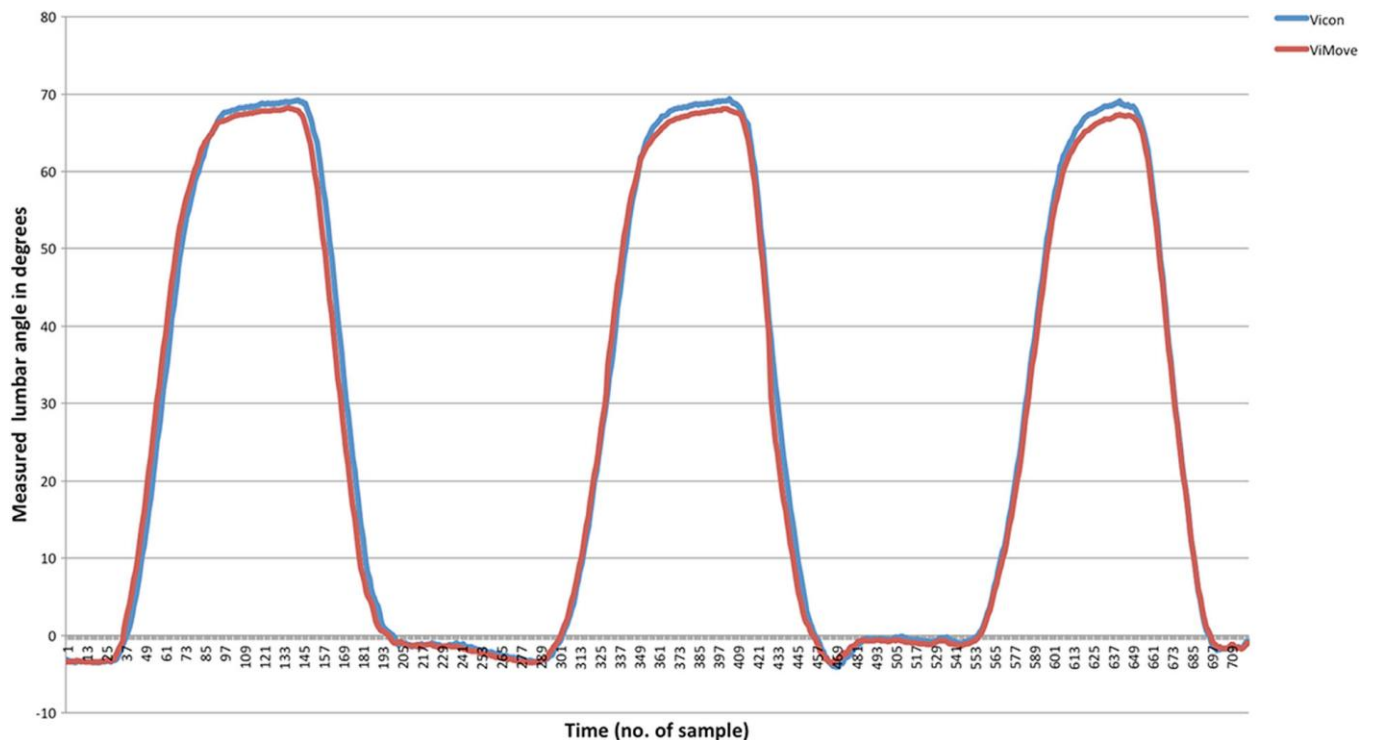
4.4.6. Limitations of motion sensor measurement of lumbo-pelvic kinematic parameters

Apart from small measurement errors, one limitation of motion sensor technology that warrants specific comment relates to skin movement artefacts. Motion sensors that adhere to the skin may demonstrate movement artefacts as well as true movement. This type of error occurs where the skin moves in a different way to the underlying musculoskeletal system, with the movement of extension particularly affected. Flexion movement creates skin stretching which increases conformity of the sensor to the skin and underlying joint movement creating relatively synchronous skin and musculoskeletal movement. In contrast, in subjects with substantial sub-cutaneous adipose tissue, skin buckling is occasionally seen in extension. Skin buckling can partly or completely distort motion sensor information. Visual inspection during movement, particularly extension, is needed to determine whether motion sensors are moving unimpeded and in the expected fashion.

4.5. Can inertial motion sensors identify atypical movement?

The paper by Laird et al. (2016) reported in this chapter provides details on the 'bandwidth' of expected variation and evidence that lumbo-pelvic kinematic parameters have sufficient stability to be potentially clinically useful. The data also showed no significant differences in movement consistency for those with and without LBP for most lumbo-pelvic kinematic parameters. There is evidence that movement-related differences exist between people with and without persistent LBP, but there is little objective data, particularly using wireless inertial motion sensors, that could characterise atypical movement. The next stage of this thesis compared a larger sample of people with and without persistent LBP, using motion sensor technology, aiming to define typical and atypical lumbo-pelvic kinematic parameters and to explore whether atypical movement was equally prevalent within the two groups.

The motion sensor system (Vimove, dorsaVi, Australia) includes wireless surface EMG data. Future reference within this thesis to the term 'lumbo-pelvic kinematic parameters' will include EMG activity of thoraco-lumbar extensor muscles. Technically, a muscle activation pattern is not specifically a lumbo-pelvic kinematic parameter that would typically refer to angular inclination, velocity, and acceleration data. However, the pattern of muscle activation activity seen in the flexion relaxation response (FRR) (described in the next chapter) directly relates to movement data and thus, for ease of reading, is included in this umbrella term.

5. Chapter 5 – Describing, defining and testing the prevalence of 'atypical' lumbo-pelvic kinematic parameters

5.1. Lumbo-pelvic kinematic parameters: utility and importance

Chapter 3 demonstrated the considerable clinical interest in lumbo-pelvic movement, and evidence that movement-related differences exist between people with and without persistent LBP. However, the nature and strength of the relationship of lumbo-pelvic movement to persistent LBP remains unclear. It is unknown if lumbo-pelvic kinematic parameters are useful or important as:

(i)   prognostic indicators that identify people without LBP who have a greater risk of developing LBP,

(ii)   factors that might identify if there are different presentations of persistent LBP that are more or less amenable to a specific intervention type (treatment effect modifier), (Mansell, GM et al., 2014), or

(iii)   factors that are potential targets of intervention due to their causal relationship with pain/activity limitation (including treatment effect mediators) (Mansell, GM et al., 2014).

From a clinical perspective, there is little information about how to distinguish between typical movement that is within an expected range and atypical movement that is outside an expected range. It would also be helpful to know the prevalence of any atypical movement. For example, it may be that some atypical parameters are frequently, rarely, or always, seen in people with persistent LBP.

5.1.1. Prognostic factors for the risk of developing of LBP

Some lumbo-pelvic movement parameters have been associated with increased risk of developing LBP. Hamberg-van Reenan et al. (2007) systematically reviewed (without meta-analysis) the relationship of trunk muscle endurance, strength and mobility of the lumbar spine and the future development of spinal pain. Their review included 23 studies and found reports of relationships between ROM and the risk of developing LBP, with two studies (Biering-Sorensen, F, 1984b; Troup, JD, 1987) indicating that a larger lumbar ROM was associated with increased risk, and three studies (Adams, MA et al., 1999; Mayer, T et al., 1984; Takala, E et al., 2000) indicating increased risk in people with a

smaller lumbar ROM. The authors concluded that, due to the inconsistent results in multiple studies, that there was inconclusive evidence for a relationship between mobility of the lumbar spine and the risk of developing LBP. It may be that both extremes of lumbar range may increase the risk of developing LBP.

Sadler et al. (2017) performed a systematic review with meta-analysis of studies that investigated musculoskeletal risk factors for LBP in prospective cohort studies. The review included 12 studies and found that reduced lateral flexion ROM, flatter lordosis and restricted hamstring length were associated with greater risk of developing LBP. Meta-analysis of lateral flexion ROM in 1,364 people (three studies) showed a significant association (odds ratio 2.44, p=0.002) between smaller lateral flexion ROM and the development of LBP. Flexion and extension ROM did not show a significant association with risk of LBP. However, consistent with other reviews, the authors noted the small number of studies, the considerable heterogeneity between study method, sample definition and measurement devices, combined to weaken findings and conclusions.

5.1.2.   Lumbo-pelvic kinematic parameters as treatment effect modifiers

Measuring movement may be important if aspects of movement can identify who is more likely to respond to an intervention. There is little research using lumbo-pelvic kinematic parameters to identify if a particular type of LBP presentation is more likely to respond to an intervention (treatment effect modifier). The visual observations of 'aberrant' movement during lumbar flexion/extension ROM and 'hypomobility' of the lumbar spine (as assessed with palpation of posterior-anterior pressure to test inter-vertebral motion) have been suggested as treatment effect moderators by Fritz et al. (2007) but without any quantifying data to differentiate between typical movement versus 'aberrant' and 'hypomobile'. Some clinical authors (O'Sullivan, P.B., 2005b; Sahrmann S., 2002) have proposed that characteristics of lumbo-pelvic rhythm such as a 75% lumbar / 25% pelvic ROM pattern or an opposite 25% lumbar / 75% pelvic ROM pattern contribution to overall trunk flexion might contribute to identifying subgroups of people with persistent LBP who have differing responses to treatment (Kim, MH et al., 2013; O'Sullivan, P.B., 2005b). However, there is little consistent empirical evidence of particular treatments of movement-based subgroups being associated with improved pain or activity limitation outcomes.

The flexion relaxation response (FRR) has been inconsistently associated with improvements in pain and activity limitation (Marshall, Paul et al., 2006; Mayer, TGMD et al., 2009; Neblett, R et al., 2014b) but has not been identified as a predictor of differential outcome.

Although not specifically known as a lumbo-pelvic kinematic parameter, the centralisation phenomenon (the relationship between repeated movement and the reduction or resolution of peripheral or spinal pain) should also be briefly noted as it has evidence as a predictor of outcome (May, S et al., 2012).

5.1.3.   Causal factors (including treatment effect mediators)

Measurement of movement-related parameters may be of value if they are on a causal pathway of LBP. No causal relationship between any movement-related parameter and **persistent** LBP has been established (Lee, H et al., 2016). Hartvigsen et al. (2018) summarised evidence on patho-anatomical characteristics and pathological conditions associated with LBP, but also found no lumbo-pelvic or movement-related parameters associated with LBP. A recent systematic meta-analysis by Lee et al. (2015) examined 12 trials of interventions for people with LBP on psycho-social and physical factors that explained the effect of pain on disability. They reported that reduced self-efficacy, psychological distress and fear were mediators of pain and activity limitation but found no physical mediators. The review also concluded that the included studies were generally underpowered for mediation analysis, most did not consider the effect of potential confounders, and that the overall methodological quality was low. Lee et al. (Lee, H et al., 2015) determined that psychological factors explained only 20-33% of the total effect, and "*that there are other unexplained causal mechanisms that are yet to be identified*" (Lee, H et al., 2016, p. 1078). It is plausible that kinematic and other movement-related parameters might contribute as causal mechanisms, but they have not been studied. While the concept of assessing parameters as mediating factors has been promoted for some time (Kraemer, H et al., 2002), there are few studies of interventions that have measured physical factors as part of their mediation analysis.

5.2.   Clinical relevance of movement

Despite the limited scientific evidence supporting a relationship between lumbo-pelvic kinematic parameters and LBP, clinicians still base intervention choice, at least in part, on observing how pain and movement respond to interventions (Dijk, M et al., 2017). Clinicians such as physiotherapists, osteopaths, exercise physiologists, and chiropractors observe movement as a component of physical

examination to discern if and how movement relates to pain. Having observed movement that is deemed problematic, a change to movement that reduces pain intensity is used to provide therapeutic guidance about the relevance of a movement-based intervention for an individual (Maitland, GD, 1986). However, little is known about the utility of kinematic information available in a detailed movement analysis, and whether this could also play a role in guiding therapy. In addition, no measurement system currently enables classification of movement as clinically typical or atypical. Clinical textbooks describe altered movement in people with persistent LBP and indicate a wide range of movement 'dysfunctions' but with little reference to objective data that could operationally define 'dysfunctional' movement (Kendall, F et al., 2005; Key, J, 2010; Sahrmann S., 2002). For instance, a person with LBP may be described as having a hypomobile ('stiff') or hyper-mobile ('overly flexible') spine but without reference to specific ROM thresholds. What would be helpful, but is currently unclear, is knowledge about what constitutes typical versus atypical movement, the prevalence of atypical movement and if the presence of atypical movement is associated with pain and/or activity limitation.

A simple concept that could be used to distinguish atypical from typical movement is to look for movement that occurs rarely. This type of approach would classify a movement as 'too much' or 'too little' if it occurred at the upper or lower end of a normal distribution of measurements. Figure 5.1 illustrates this concept.

Figure 5.1 Defining atypical movement
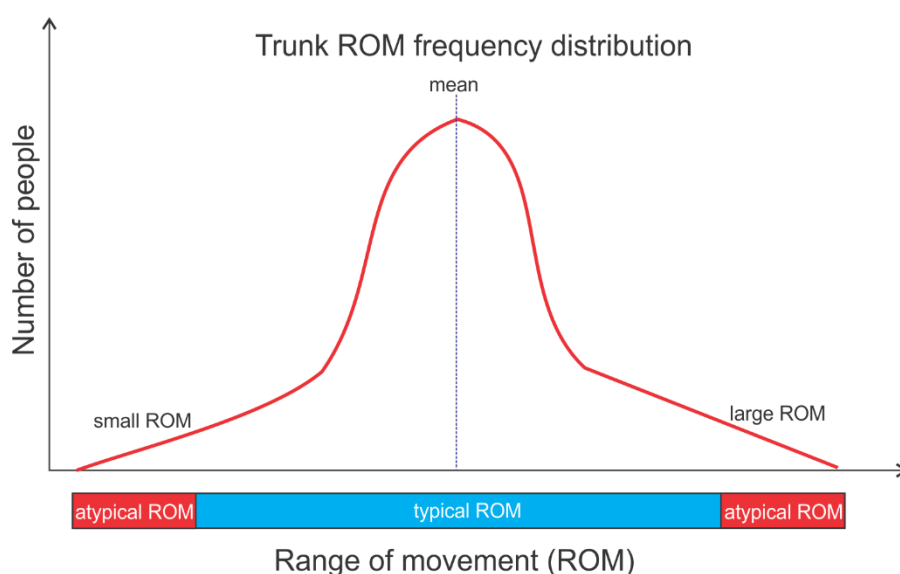
5.3. Exploring movement characteristics in people with and without LBP

With the advent of wireless motion sensor technology that is usable in a clinical setting, it is possible to quantify highly detailed lumbo-pelvic kinematic parameters. This has created a capacity for measurements to be analysed and classified as typical or atypical, including such lumbo-pelvic kinematic parameters such as peak angular ROM at T12 (representing lower trunk angular displacement), lumbar spine and pelvic angular displacement at S2 (representing hip movement), velocity (duration of movement), timing and sequence of regional contributions, and patterns of lumbar extensor muscle activation (FRR) during movement.

 Therefore, an exploratory study was designed to:

(i)   define the lumbo-pelvic movement parameters that are measurable with the Vimove system,

(ii)   describe a system for differentiating between typical and atypical movement,

(iii)   describe the prevalence of atypical movement parameters in people with and without LBP.

In order to create a standardised method for ongoing investigations of this nature, this empirical study was limited to flexion-related lumbo-pelvic kinematic parameters. This reduced the complexity that would arise if multiple planes of movement were studied. Flexion was also considered a suitable first target for investigation as flexion-related activities, including sitting, are the most commonly reported aggravating activities in people with persistent LBP (O'Sullivan, K et al., 2012; Pengel, LH et al., 2004).

The following paper has been reproduced and submitted to BMC Musculoskeletal Disorders, 2018, complete with amendments requested by reviewers and has been referenced as:

Laird, R., Kent, P., Li, P., Ussing, K., & Keating, J. (2018A). Does movement matter in people with back pain? Investigating 'atypical' lumbo-pelvic kinematics in people with and without back pain using wireless movement sensors. *BMC Musculoskeletal Disorders, submitted*.

5.4. Does movement matter in people with back pain? Investigating 'atypical' lumbo-pelvic kinematics in people with and without back pain using wireless movement sensors

Robert A Laird[1]
Email :█████████████████

Peter Kent[2,3]
Email:█████████████████

Kasper Ussing[4]

Email:███████████████

Paoline Li[5]

Email:████████████████

Jennifer L Keating[1]
Email:███████████████

[1] Department of Physiotherapy, Monash University, PO Box 527, Frankston, Victoria 3199, Australia

[2] School of Physiotherapy and Exercise Science, Curtin University, Perth, Australia

[3] Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark

[4] Spine Centre of Southern Denmark, Hospital of Lillebaelt, Middelfart, Denmark

[5] SuperSpine Physiotherapy, 380 Springvale Rd, Forest Hill, 3131, Australia

Postal Address:

* Corresponding author. Robert Laird, 380 Springvale Rd, Forest Hill, 3131 Melbourne, Victoria, Australia

5.4.1. Abstract

Background

Interventions for low back pain (LBP) commonly target 'dysfunctional' or atypical lumbo-pelvic kinematics in the belief that correcting aberrant movement improves patients' pain and activity outcomes. If atypical kinematic parameters and postures have a relationship to LBP, they could be expected to more prevalent in people with LBP compared to people without LBP (NoLBP). This

exploratory study measured, defined and compared atypical kinematic parameters in people with and without LBP.

Methods

Wireless inertial motion and EMG sensors were used to measure lumbo-pelvic kinematics during standing trunk flexion (range of motion (ROM), timing, sequence coordination, and extensor muscle activation) and in sitting (relative sitting position, pelvic tilt range) in a sample of 126 of adults without LBP and 140 chronic LBP subjects. Atypical movement was defined using the 10th/90th centiles of the NoLBP group. Mean differences and prevalence rates for atypical movement were calculated. Dichotomised pain scores for 'high-pain-on-bending' and 'high-pain-on-sitting' were tested for their association with atypical kinematic variables.

Results

For standing flexion, significant mean differences, after adjusting for age and sex factors, were seen for the LBP group with (i) reduced ROM (trunk flexion (NoLBP 111°, LBP 93°, p<.0001), lumbar flexion (NoLBP 52°, LBP 46°, p<.0001), pelvic flexion (NoLBP 59°, LBP 48°, p<.0001), (ii) greater extensor muscle activation for the LBP group (NoLBP 0.012, LBP 0.25 p<.0001), (iii) a greater delay in pelvic motion at the onset of flexion (NoLBP -0.21 sec; LBP -0.36 sec, p=0.023), (iv) and longer movement duration for the LBP group (NoLBP 2.28 sec; LBP 3.18 sec, p<.0001). Atypical movement was significantly more prevalent in the LBP group for small trunk (x5.4), lumbar (x3.0) and pelvic ROM (x3.9), low FRR (x4.9), delayed pelvic motion at 20° flexion (x2.9), and longer movement duration (x4.7). No differences between groups were seen for any sitting parameters. High pain intensity was significantly associated with small lumbar ROM and pelvic ROM.

Conclusion

Significant movement differences during flexion were seen in people with LBP, with a higher prevalence of small ROM, slower movement, delayed pelvic movement and greater lumbar extensor muscle activation but without differences for any sitting parameter.

Keywords: Low back pain, Movement disorders, range of movement (ROM), Flexion relaxation, Lumbo-pelvic rhythm, Velocity

Does movement matter in people with back pain? Investigating 'atypical' lumbo-pelvic kinematics in people with and without back pain using wireless movement sensors

5.4.2. Introduction and background

Many clinicians use movement-related interventions to treat low back pain (LBP) based on a view that there is a relationship between back pain and dysfunctional movement. There is some evidence that interventions designed to modify movement behaviour are associated with improvements to pain and activity limitation in chronic LBP (Fersum, KV et al., 2012; Kent, P et al., 2015a). However, these studies have typically quantified changes to pain and activity limitation but not changes to movement qualities, so the relationship between change in movement behaviour and changes in pain and function is not clear.

The movement qualities of people with LBP have been observed to differ from those without LBP in a number of ways, including smaller range and lower speed of lumbar motion (Laird, R et al., 2014), differences in muscle size, recruitment and relaxation patterns (Hides, J et al., 2008; Hodges, P et al., 1996; Neblett, R et al., 2003; Nelson-Wong, E et al., 2012; Nelson-Wong, E et al., 2014), different breathing patterns (Grenier, SG et al., 2008; Grimstone, SK et al., 2003; Kell, RT et al., 2006; Lamberg, EM et al., 2012), poorer proprioception (Lee, AS et al., 2010; Newcomer, KL et al., 2000; O'Sullivan, PB et al., 2003), less motor control variability (Abboud, J et al., 2014; Hodges, P et al., 2009; Hodges, PW et al., 2013; Moseley, GL et al., 2006; Villumsen, M et al., 2016), poorer strength, endurance and muscle force control (Pranata, A et al., 2017; Steele, J et al., 2014) and different patterns of flexion-related lumbo-pelvic movement (Kim, M., et al., 2013). Although there is evidence of different movement qualities in people with back pain, there is little consensus about which movement attributes are important, how frequently they are seen, or whether movement difference might cause, or be caused by, LBP.

Recent movement research has mostly used some type of opto-electronic measurement, often in a laboratory setting, however wireless inertial motion and electromyography sensors that measure movement are now available and practical for use in both clinical and every-day-life settings. Inertial motion sensors are capable of providing detailed, precise kinematic information that is not easily measured by visual observation or through basic measurement tools, such as goniometers or flexible rulers. This 'higher definition' information provides a detailed picture of the magnitude, regional

contributions and 'quality' of movement. Kinematic parameters such as relative range of movement (ROM) of body regions (e.g. lumbar spine versus pelvic movement), symmetry of ROM, movement speed, sequencing and timing of regional contributions (i.e. do lumbar and pelvic contributions move synchronously), pelvic tilt kinematics (such as tilt angles, range from full anterior to full posterior tilt, trunk versus pelvic movement during tilting etc), can be combined with surface electromyographic (sEMG) information about lumbar or other muscle activation during movement. However, the clinical relevance of such kinematic parameters remains unclear. If kinematic parameters have a relationship to LBP, causal or consequential, they should be more prevalent in people with LBP than in those without LBP, even if not all people with LBP have the same movement characteristics.

A common clinical practice is to identify movement that is painful and/or 'atypical'. A simple example would be to classify atypical ROM by identifying people whose ROM is particularly small or large, relative to a population without back pain. A similar process of classifying movement as atypical could be applied to movement timing, lumbo-pelvic rhythm (e.g. the sequence and pattern of lumbar versus pelvic contribution to movement during flexion) and muscle activation parameters. Exploratory analysis of detailed kinematic assessment and the prevalence of atypical movement may provide empirical evidence to inform and clarify the clinical practice of attempting to differentiate atypical from normal movement.

This exploratory study had four aims:

1. To **describe** the lumbo-pelvic kinematic parameters that can be measured with wearable inertial motion sensors, when investigated in two clinically-relevant types of lumbo-pelvic function: flexion (assessed during standing forward bending) and sitting.

2. To **explore and define** criteria that could classify these kinematic parameters as typical or atypical.

3. To **investigate** and **compare** the prevalence of atypical kinematic parameters in people with LBP, (LBP group), and people who have never had back pain (NoLBP group).

4. To examine the relationship between atypical kinematic parameters and pain reported during standing forward bending or sitting activities.

We limited this initial, exploratory investigation to the analysis of flexion and sitting kinematic parameters only, to develop and test a method for classifying movement as atypical, and to compare the prevalence of atypical kinematic parameters in people with and without LBP. Lumbo-pelvic flexion has a relatively

151

large range of motion compared to other physiological movements, has kinematic parameters of timing and sequence that are of potential clinical interest, and is often implicated as problematic in functional activities such as bending and lifting. Sitting kinematics were also included because sitting is often associated with LBP and because there is a belief that sitting posture is associated with LBP (O'Sullivan, K et al., 2012).

As we do not have a clear understanding of what represents atypical movement, this study was exploratory and descriptive, without pre-specified hypotheses.

5.4.3. Method

Study design and participant selection: inclusion and exclusion criteria.

We used an observational, cross-sectional design for this exploratory study. Participants with and without back pain were recruited. Participants without back pain (NoLBP) were recruited by poster, email and word-of-mouth advertising from universities, workplaces and community groups. Inclusion criteria were defined: 18-65 years of age, no significant health issues that would affect movement, and no history of any LBP episode that required visiting a health professional or taking time off either work or usual sport.

Participants with current back ± leg pain (LBP) were recruited using poster and word-of-mouth advertising from three Australian physiotherapy clinics/outpatient departments in primary and secondary care in 2014-2107. They were also recruited during 2011 at the Medical Department of the Spine Centre of Southern Denmark, which is an outpatient secondary care hospital department. All participants were measured at the site of recruitment. The inclusion and exclusion criteria, measurement protocols and test procedures have previously been reported in detail (Laird, R et al., 2016) for the Australian sample and the same procedures were used in the Danish sample. In summary, adults with LBP were included if they had LBP for > 3 months, scored > 2/10 for pain intensity on a numerical rating scale, and excluded if they had previous lumbar surgery or invasive spinal procedures for LBP, including therapeutic injections, within the last 12 months, any serious medical or musculoskeletal issues that had the potential to affect the lumbo-pelvic region, an implanted electrical medical device, a BMI > 30 (where it becomes difficult to palpate bony landmarks) or were pregnant. All potential participants were screened for suitability by a trained administrator, by direct contact and follow-up phone call if clarification was required, and then invited to participate. Ethics approval was

obtained from Monash University Human Research Ethics Committee (approval number 2016-1100) and from The Regional Committees on Health Research Ethics for Southern Denmark (approval number S-20110071). All participants gave written informed consent.

Measurement protocol and test procedures

Each participant completed an 11 point numerical pain rating scale (scores 0-10 where 10 = maximum pain intensity) (Ross, R et al., 1997), a 24 question Roland Morris Disability Questionnaire (RMDQ-24) (Roland, M et al., 2000) scored as a percentage with 100% = maximum activity limitation (Kent, P et al., 2011) and a specifically designed questionnaire about direction-specific pain (see Appendix 1) prior to testing. All participants attended a single test session, where they were partially undressed to expose the body from T12 to the posterior superior iliac spines (PSIS). Shoes were removed. Two motion sensors were then applied at T12 and S2 using adhesive backings and two surface electromyography (EMG) sensors were placed 1.5cm either side of the L3 spinous process (see Figure 1). A patient-height adjusted, plastic template was used to assist placement. A standardized testing procedure, including palpation of bony landmarks, device application and verbal instruction, was performed by six trained physiotherapists and three final year physiotherapy students, all of whom had received at least three hours specific training to minimize differences between testers. Reliability data has previously been published (Laird, R et al., 2016; Ronchi, A et al., 2008). With each participant, a single practice of the standing flexion movement was initially performed to test that sensors were working correctly and to adjust calibration. Subsequently, a minimum of three flexion repetitions were performed. The participant stood in a comfortable position and was instructed to bend forwards to the fully flexed position at their natural speed and hold this position for three seconds period using a counted time signal before return to upright standing. They then assumed three sitting postures, usual, upright and slumped, each for 15 seconds, with data captured in the last 5 second period. Lastly, while still sitting, they performed three repetitions of pelvic tilt. Testing protocols and movements can be viewed in Appendix O. All kinematic data were automatically captured at 20Hz by the ViMove system, independently of the assessor, and exported from the ViMove software as raw data, along with a system-generated graphic representation of data.

Figure 5.2 Sensor placement

An example of sensor placement with the lower border of the upper sensor placed at the T12 level, the upper border of the lower sensor level with S1 and the EMG sensors placed over lumbar extensor muscles at the level of L3.

Details and definition of kinematic characteristics

Eleven flexion and three sitting kinematic parameters were selected a priori for assessment and are summarised in Table 5.1 and described in detail in the subsequent text.

Table 5.1 Details of lumbo-pelvic kinematic parameters investigated

Standing flexion kinematic parameters	Measurement Units
Trunk angular inclination at T12 (upper motion sensor)	Degrees
Pelvic angular inclination at S2 (lower motion sensor	Degrees
Lumbar range of motion (difference between T12 and S2 sensors)	Degrees
Lumbo-pelvic coordination (rhythm) – peak angle, lumbar percentage	Percentage
Lumbo-pelvic coordination (rhythm) – across all movement, lumbar percentage	Percentage
Flexion relaxation response	Ratio
Delay (lag) of pelvic or lumbar movement at onset	Time (seconds)
Delay (lag) of pelvic or lumbar movement at 20° of angular inclination	Time (seconds)
Delay (lag) of pelvic or lumbar movement at 30° of angular inclination	Time (seconds)
Delay (lag) of pelvic or lumbar movement at 40° of angular inclination	Time (seconds)
Duration of flexion movement (from standing to full flexion)	Time (seconds)
Sitting kinematic parameters	
Sitting pelvic tilt angular inclination range at S2	Degrees
Pelvic tilt ratio (maximum S2 movement / maximum T12 movement)	Ratio
'Relative' lumbar ROM in sitting	Degrees

Range of motion (ROM)

Trunk ROM was measured as angular inclination of the trunk at T12, pelvic ROM was measured as angular inclination of the pelvis at S2 and lumbar ROM was calculated using the difference between the angular inclinations at T12 and S2.

Lumbo-pelvic Coordination (rhythm)

Lumbo-pelvic coordination, sometimes described as lumbo-pelvic rhythm, is a method of describing lumbar versus pelvic contributions to movement. We calculated the relative contribution of lumbar movement and compared two methods (i) using peak angles at the end range of trunk flexion by using lumbar peak angle divided by trunk peak angle and expressed as a percentage, and (ii) using 'area-under-the-curve' method which sums all lumbar ROM and all pelvic angular inclination at 20 samples per second from the start of flexion to a return to standing.

Flexion relaxation response (FRR)

A common pattern of thoraco-lumbar extensor muscle activity measured by surface electromyography (sEMG) is seen in people without back pain with electrical activity occurring at the start of trunk flexion (eccentric activation) and again on return from the fully flexed position (concentric activity), with minimal or no activity in the fully flexed position. This has been described as the flexion relaxation response (FRR) (Floyd, W et al., 1951). Flexion relaxation is often absent in people with LBP when compared to people without LBP, and when restored, is associated with improvements in pain and activity limitation (Geisser, ME et al., 2005; Neblett, R et al., 2014a). It is possible that higher extensor muscle activity in the fully flexed position, a position that is recognized as a biomechanically vulnerable position for the intervertebral disc (O'Connell, GD et al., 2011), increases compressive loading. This study calculated the FRR ratio (following published methods (Ahern, DK et al., 1988; Marshall, Paul et al., 2006; Watson, P et al., 1997)) using the sum of sEMG activity (millivolts) during 3 seconds in the fully flexed position (numerator) divided by the summed sEMG activity during both the eccentric (forward bending) and concentric (returning to upright stance) phases of flexion (denominator), (see Figure 5.3). The 'normal' complete muscle relaxation in full flexion would result in the FRR being close to or equal to zero. Any muscle activity during end-range flexion increases this ratio, with a larger number indicating greater muscle activation and reduced relaxation in the fully flexed position. Raw sEMG activity (microvolts) was sampled at 300Hz, then a high pass filtering was applied using a 'fast fourier transformation' algorithm. A low pass filtering occurred to create an envelope of the signal at 20Hz. Finally, the signal was transformed using a root-mean-square (RMS) process to measure muscle activity.

Figure 5.3 Flexion relaxation ratio definition and calculation
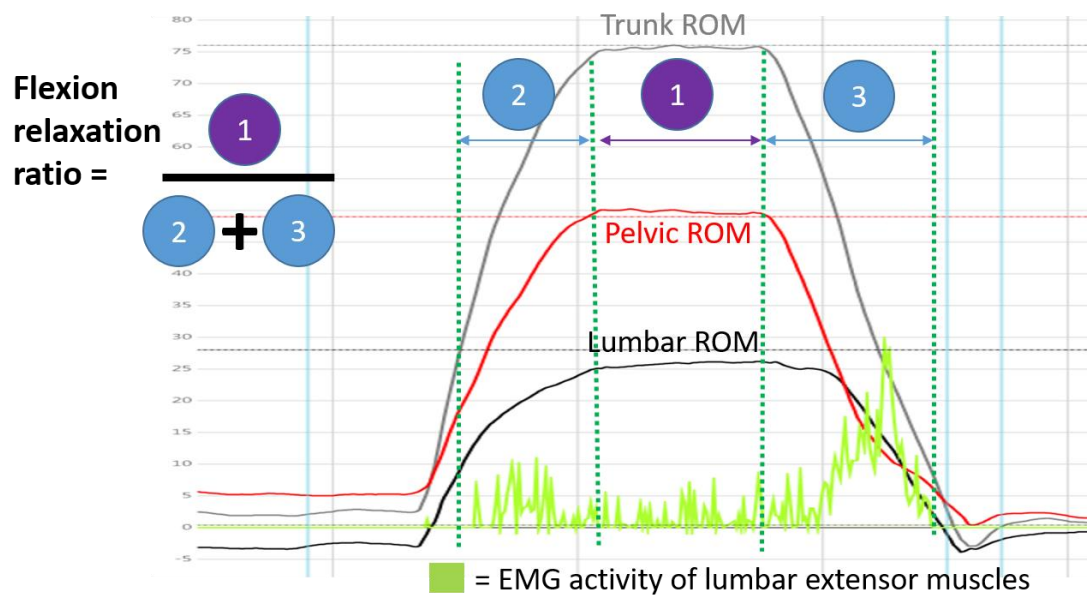
Figure 5.3: The flexion relaxation ratio is calculated by dividing EMG activity while the subject is fully flexed for 3 seconds (numerator) by the sum of EMG activity in the eccentric plus concentric phases of flexion (denominator).

'Delay' (lag) between pelvic and lumbar movement

Because motion sensors measure movement over time, it is possible to assess time-related synchronicity of lumbar versus pelvic contributions to flexion movement. There is evidence of time-related differences in lumbar versus pelvic movement during flexion (Wong, TK et al., 2004). An 'onset-delay' parameter measures which region, lumbar or pelvis, moves first and the time 'gap' between regions. Negative numbers indicate a delay in pelvic motion, with movement initiated first in the lumbar spine, while positive numbers indicate a delay in lumbar motion, with movement initiated at the pelvis. Larger numbers indicate a longer delay. The start of flexion was defined as the point at which velocity was > 7°/sec (the velocity required before movement was visible graphically).

Figure 5.4 Delay (lag) of pelvic compared to lumbar movement
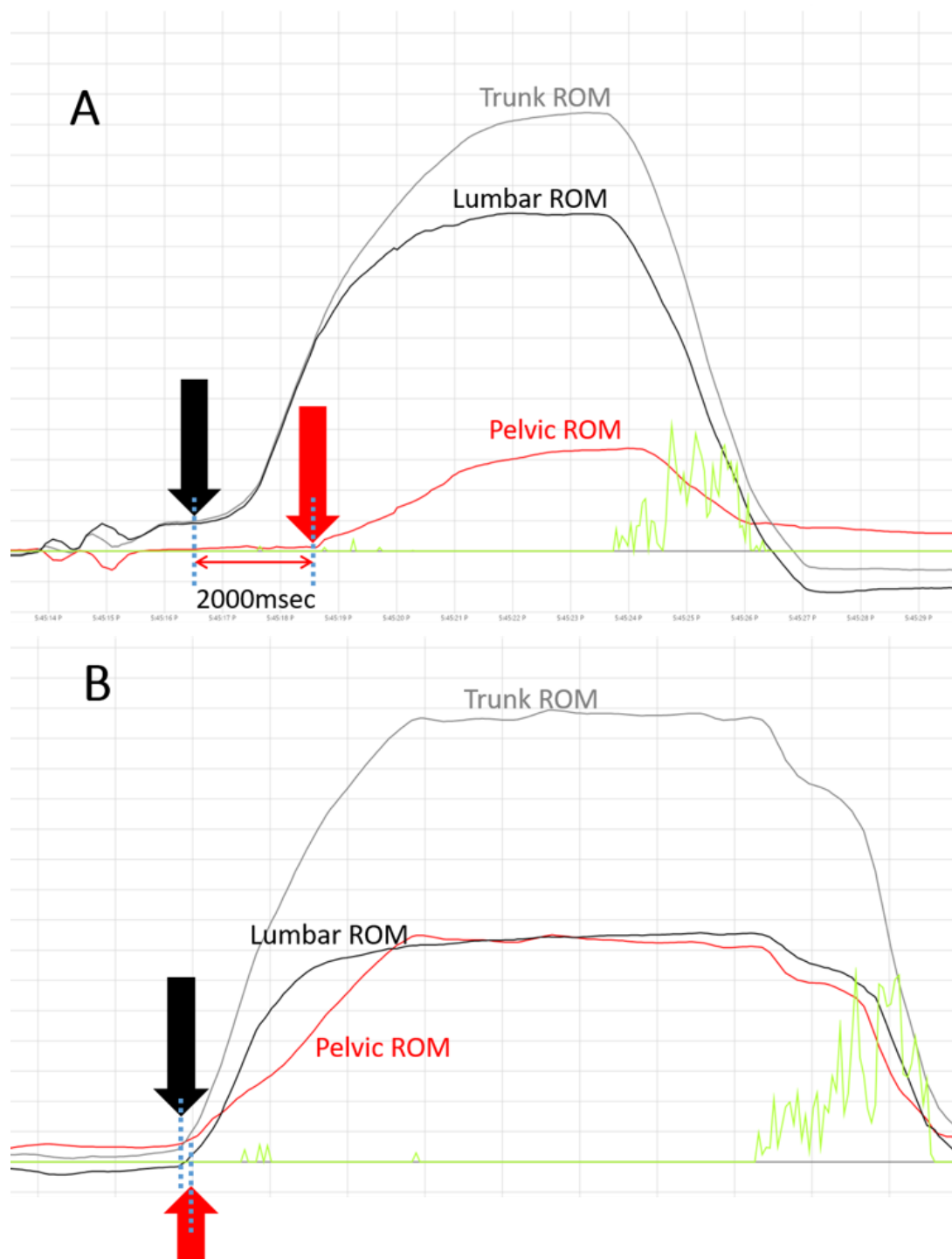
Figure 5.4: These graphs show ROM (Y axis) changes over time (X axis). Graph A was from a subject who moved their lumbar spine into flexion with a two second delay before the pelvis started moving. Graph B shows a more typical pattern with a synchronous start of movement of the lumbar spine and pelvis.

Figure 5.4 demonstrates an example of an onset-delay in pelvic movement. The 'delay-at 20°, 30° and 40°' parameters provide a similar view of movement discrepancy and is a calculation of the time needed to achieve 20°, 30° and 40° of angular inclination from the start of movement, for each region. These parameters provide a measure of time-related synchronicity (or lack thereof) of lumbar versus pelvic contribution to flexion.

Flexion movement duration

Flexion movement duration was defined as the time taken from start of trunk flexion (when velocity of movement was >7°/sec) to the fully flexed position (when velocity was <7°/sec velocity). We defined end of trunk flexion in this way because movement with a velocity less than 7°/sec is very close to end-range and this threshold minimizes error that can result from the peak angle slowly increasing due to creep when the fully flexed position is sustained for the three second period during which we assessed the flexion relaxation response.

Sitting: Pelvic tilt range and pelvic tilt ratio

Pelvic tilt ROM (from full posterior to anterior tilt angular inclination) may be of clinical interest when sitting is associated with pain. Reduced pelvic repositioning accuracy (proprioception) and reduced movement variability have been identified in people with chronic LBP (Abboud, J et al., 2014; Hodges, PW et al., 2013; Laird, R et al., 2014; Seay, JF et al., 2011; Villumsen, M et al., 2016). The pelvic tilt range was measured by calculating the angular inclination of the pelvis between full anterior and full posterior tilt, which provided estimates of lower lumbar movement. The pelvic tilt ratio is a measure of the independence of pelvic tilt relative to trunk movement and is calculated by dividing the angular inclination of the pelvic sensor by the angular inclination of the trunk sensor. This parameter was used to test how pelvic tilting was performed i.e. whether movement was independently performed only in the lower lumbar motion or combined with upper lumbar motion, as might occur if a subject simultaneously moved the trunk into flexion while performing posterior pelvic tilt). A number > 1 indicates larger pelvic than trunk ROM; a number <1 indicates larger trunk than pelvic ROM during the pelvic tilt manoeuvre.

Sitting: relative position

Measurements were made of usual, full slumped (kyphotic) and full upright (lordotic) sitting lumbar positions. The relative sitting position was calculated for usual sitting by deeming the fully slumped

sitting position to be 100% and the fully upright sitting to be 0%. For example, if full slump was at 50° of lumbar flexion and full upright sitting was at 0° lumbar flexion, then the difference (50°-0°=50°) between maximum slump and upright sitting would represent 100% of the available ROM. If usual sitting was 25°, the relative sitting position would have been coded as 50%. This index enabled comparisons between individuals for defining usual sitting position relative to the available range of pelvic movement.

Pain scores for bending and sitting activity

In addition to a numerical rating scale for pain, people with back pain were asked, using a self-completed, non-validated questionnaire "Is your pain aggravated by bending forwards activities?", scored as (0) never, (1) rarely (2) sometimes, (3) often, (4) always and then a further multiple choice based on the level of pain aggravation: (0) none, (1) low, (2) medium, (3) high. An overall score was calculated by multiplying the two answers to give scores ranging from 0 to 12. We used this method, despite having only face validity, as it reflects the common clinical practice of establishing the severity and frequency of pain associated with aggravating activities. Scores were then arbitrarily dichotomized a priori, into <6 or 6 or greater. Similarly, a 'pain on sitting' score was derived by asking "How long can you sit before feel you have to stand up?" (<5min, 10, 20, 30, 60 or > 60min), scored 5-0 and "If pain stops you from sitting any longer, what is your level of pain?" on a scale of 0-10. A total score for sitting was calculated by multiplying the two sitting scores for a maximum score of 50 which was then dichotomized to 18 or greater based on the arbitrary choice of the median score. A copy of this questionnaire can be viewed in Appendix N.

Equipment

The ViMove system, version 5, (DorsaVi, Australia) is an inertial measurement system comprised of two wireless movement sensors containing a triaxial accelerometer, a triaxial gyroscope and a magnetometer, two wireless surface EMG sensors, and a small wireless recording device that can be easily carried (e.g. in a pocket). Average differences of <2° have been reported for through-range flexion movements when compared to a VICON opto-electronic device (Mjøsund HL et al., 2017). The ViMove version 5 movement sensors collected data at 20 Hz.

Sample size

As this was an exploratory study, no data were available for sample size calculations. The aim was to test a sample large enough to enable the development of hypotheses but not so large as to waste

resources should there be no interpretable findings. Samples of over 100 per comparison group were considered large enough to indicate the likelihood of observable patterns in the data and provide insight into sample sizes required to test hypotheses arising from this work. As subjects in both Australia and Denmark were assessed using the same procedures, their data were pooled to maximise data available for analysis.

Data analysis

Data were analysed from Danish data collected during 2011 using version 4.5 of the ViMove software and Australian data collected between 2014 to 2017 using version 5.10. The software version did not affect the nature the data or its accuracy. Movement data were exported from the ViMove software into Excel spreadsheets (Microsoft Corp, Redmond, WA USA) for data cleaning and graphical visualisation (for an example, see Figure 2 and 3). Each data capture was visually checked for accuracy and the first three repetitions of each movement were averaged to improve consistency.

Statistical analysis

Movement data were analysed using multivariable linear regression to examine the effects of group (LBP, noLBP), with age and sex included as co-variates in the model. Each kinematic characteristic was then dichotomized into atypical or typical using the arbitrary cut-point of the 10th centile value derived from the NoLBP group. For each parameter, the lowest 10% of values in the NoLBP group was classified as atypically small and the remaining 90% of values classified as typical. A similar logic was applied in interpreting the highest 10% of values as atypically large. The frequency of atypical movement was then reported for each group. As age and sex are known to be associated with range of movement (Intolo, P et al., 2009; Laird, R et al., 2014), age and sex adjusted prevalence ratios were calculated using logistic regression, with the resultant odds ratios being converted into prevalence ratios using the STATA oddsrisk command. Dichotomised pain scores for 'high-pain-on-bending' and 'high-pain-on-sitting' were tested for their association with atypical kinematic variables using logistic regression. STATA 14.0 was used for all statistical analysis (StataCorp, College Station TX, USA).

5.4.4. Results

Demographics

Participant sex and age are presented in Table 5.2. There were 24 NoLBP and 35 LBP Danish subjects. There was no difference in age, sex or BMI between Australian and Danish subjects. For the LBP group, the mean pain score (and standard deviations) on a 0-10 scale was 5.3 (1.5) and activity limitation (RMDQ-24 transformed to a 0-100 scale) was 39 (21). There was a significant difference in age, with people with LBP being, on average, 7 years older than people with no back pain. However, on all the movement parameters, there were no statistically significant associations between the prevalence of atypical movement in the LBP and NoLBP groups and either age or sex. This was also reflected by the unadjusted and adjusted (age and sex) prevalence ratios being almost identical (data not shown).

Due to software version evolution between 2011 and 2014, time related and sitting data could only be analysed for people analysed after 2014 (LBP group = 105 and NoLBP = 100). The range of movement related data, including lumbo-pelvic rhythm and flexion relaxation response, were available for all participants.

Table 5.2 Demographics of LBP and NoLBP participants

	N (for ROM, LPR and FRR)*	**N** (for time-related and sitting data)	**Age** (mean ± SD)	**Sex**
NoLBP	126	100	34.4 ± 13.5**	41% Male
LBP	140	105	41.4 ± 12.6**	43% Male

ROM = range of motion, LPR = lumbo-pelvic rhythm, FRR = flexion relaxation response

*** p=.0001*

Flexion kinematic data

Between group comparisons (mean, standard deviations, 10th and 90th percentiles) for all flexion kinematic data are reported in Table 5.3 and 5.4.

Peak angular data

Significant mean (SD) differences between the NoLBP and LBP groups were found for trunk peak angle (NoLBP 111o (16o); LBP 93o (16o), p<.0001), lumbar peak angle (NoLBP 52o (11o); LBP 46o (12o), p<.0001) and pelvic peak angle (NoLBP 59o (15o); LBP 48o, (15o), p<.0001) (Table 3). People with a small ROM were 5.4 (95%CI 3.0-9.7, p<.0001) times more prevalent in the LBP group for trunk ROM

when adjusted for age and sex differences. Similar values were seen for lumbar and pelvic ROM (Table 2). There was no difference in the prevalence of atypically large ROM between groups for trunk, lumbar or pelvic angles (see Table 5.3).

Lumbo-pelvic rhythm (LPR)

There were no differences between groups for the percentage of lumbar (versus pelvic) contribution to overall trunk flexion movements, and minimal, non-significant differences in prevalence rates when both low and high lumbar percentage contribution were compared (Table 5.3) when using both peak angle and area-under-the curve methods. There was no difference in the results from the two methods of calculating the percentage of lumbar contribution, so the less complex approach of peak angle was reported and the more complex calculation method using the area-under-the-curve approach was dropped from further reporting.

Flexion relaxation response (FRR)

Significant differences between the NoLBP and LBP groups were found for a low FRR ratio (NoLBP 0.012, (0.32); LBP 0.25, (0.32), p<.0001) indicating a greater loss of flexion relaxation in the fully flexed position for the LBP group. The prevalence of low FRR (greater activity of extensor muscle in the fully flexed position) was 4.9 (95%CI 2.9-8.4, p<.0001) times greater in the LBP group when compared to the NoLBP group (Table 5.3).

Onset delay and at 20° of trunk movement

The time difference comparing lumbar to pelvic movement reaching 20° of angular inclination was reported, and the alternative computation of comparisons at 30° and 40° were dropped, as almost all participants produced a reading of 20° for both lumbar and pelvic movement, whereas at 30° and 40°, 13% and 33% of participants respectively did not achieve these angles for either lumbar or pelvic motion. Significant differences between the NoLBP and LBP groups were found for 'onset-delay', with a between group difference of greater delay in pelvic motion for the LBP group (NoLBP -0.21, (0.46)sec; LBP -0.36, (0.46)sec, p=0.023). There were no significant differences in atypically delayed lumbar or pelvic movement at onset. Atypical 'delay-at 20o' for pelvic movement was significantly more prevalent (2.9 times) in the LBP group (95%CI 1.5-5.6, p=.0007) (Table 5.4).

Flexion movement duration

Significant differences between the NoLBP and LBP groups were found for flexion movement duration (NoLBP 2.28 (0.94)sec; LBP 3.18 (0.94)sec, p<.0001). The prevalence of atypically long flexion movement duration (slow trunk movement) was 4.7 (95%CI 2.5-8.7, p<.0001) times greater in the LBP group than for the NoLBP group (Table 5.4).

Sitting: Pelvic tilt range and relative sitting position

There were no differences found for pelvic tilt range, pelvic tilt ratio or for relative sitting position between groups. There were no between group differences in the prevalence of atypical sitting parameters (Table 5.4).

Relationship between pain scores and atypical flexion or sitting movement

There was a significantly greater frequency of higher pain scores on bending in people with small lumbar ROM or small pelvic ROM. No other flexion or sitting kinematic parameter demonstrated differences in the frequency of high pain scores between the NoLBP and LBP groups (Table 5.5). Five LBP subjects had incomplete pain scores and therefore were not included in that analysis.

Table 5.3 Range of movement, lumbo-pelvic rhythm and FRR parameters

Movement parameter	Details	No LBP (n=124)	LBP (n=140)	p-value
Peak trunk flexion	Trunk flexion angular inclination (T12)	111° ± 16°	93° ± 16°	p<.0001
Small trunk ROM (10th centile, <93°)	Number (%) of people with **small trunk flexion**	11 (10%)	67 (47.8%)	p<.0001
	Prevalence ratio*	-	5.4 (3.5-7.3)	
Large trunk ROM (90th centile, >128°)	Number (%) of people with **large trunk flexion**	12 (10%)	4 (3%)	p=.008
	Prevalence ratio	-	0.3 (0.1-0.9)	
Peak lumbar flexion	Lumbar ROM	52° ± 11°	46° ± 12°	p<.0001
Small lumbar ROM (10th centile, <39°)	Number (%) of people with **small lumbar flexion**	12 (10%)	41 (29.3%)	P=.0001
	Prevalence ratio	-	3.0 (1.8-4.7)	
Large lumbar ROM (90th centile, >65°)	Number (%) of people with **large lumbar flexion**	13 (10%)	8 (6%)	NS
	Prevalence ratio	-	0.5 (0.2-1.2)	
Peak pelvic flexion	Pelvic flexion angular inclinication (S2)	59° ± 15°	48° ± 15°	p<.0001
Small pelvic ROM (10th centile, <42°)	Number (%) of people with **small pelvic flexion**	10 (9%)	48 (34%)	p<.0001
	Prevalence ratio	-	3.9 (2.3-5.8)	
Large pelvic ROM (90th centile, >75°)	Number (%) of people with **large pelvic flexion**	13 (10%)	7 (5%)	NS
	Prevalence ratio	-	0.5 (0.2-1.1)	
Lumbo-pelvic co-ordination	Mean Lumbar % contribution	48 ± 11%	49 ± 11%	NS
Small Lx contribution (10th centile, <38%)	Number (%) of people with **small lumbar contribution**	13 (10%)	19 (14%)	NS
	Prevalence ratio	-	1.3 (0.7-2.4)	
Large Lx contribution (90th centile, >63%)	Number (%) of people with **large lumbar contribution**	11 (9%)	18 (13%)	NS
	Prevalence ratio	-	1.5 (0.7-2.8)	
FRR	Means units of surface EMG activity	0.012 ± 0.32	0.25 ± 0.32	p<.0001
Low FRR (10th centile, >0.033 units of EMG activity)	Number (%) of people with **reduced FRR**	13 (9%)	71 (52%)	p<.0001
	Prevalence ratio	-	4.9 (3.4-6.4)	

Table 5.4 Timing and sitting parameters

Movement parameter	Details	No LBP (n=100)	LBP (n=105)	p-value
Delay at 0°	Mean delay (negative numbers indicate pelvic delay)	-0.21 ± 0.46sec	-0.36 ± 0.46sec	p=.023
Pelvic delay at onset of movement (10th centile, >0.53sec)	Number (%) of people with **pelvic delay > 0.53sec**	10 (10%)	19(18%)	NS
	Prevalence ratio	-	2.0 (0.9-3.3)	
Lumbar delay at onset of movement (90th centile, >0sec)	Number (%) of people with **lumbar delay >0sec**	11 (11%)	10 (10%)	NS
	Prevalence ratio	-	1.1 (0.04-0.8)	
Delay at 20°	Mean delay (negative numbers indicate pelvic delay)	-0.30 ± 0.88sec	-0.51±0.90sec	NS
Pelvic delay at 20° of trunk flexion (10th centile, >0.81sec	Number (%) of people with **pelvic delay > 0.81sec**	10 (10%)	29 (29%)	p=.0007
	Prevalence ratio		2.9 (1.6-4.7)	
Lumbar delay (90th centile, >0.15sec)	Number (%) of people with **lumbar delay >.15sec**	9 (9%)	18 (18%)	NS
	Prevalence ratio		2 (0.9-3.8)	
Mean movement duration	Time from start of flexion to full flexion	2.28±0.94	3.18±0.94	p<.0000
Slow Trunk movement (10th centile, >3.12 seconds)	Number (%) of people with **Slow Trunk movement**	10 (10%)	49 (47%)	p<.0000
	Prevalence ratio	-	4.7 (2.9-6.5)	
Mean pelvic tilt range	Range from full anterior tilt to full posterior tilt	29° ± 13°	29° ± 13°	NS
Small pelvic ROM (10th centile, < 11°)	Number (%) of people with **small pelvic tilt** range	10 (10%)	10 (10%)	NS
	Prevalence ratio	-	1.0 (0.4-2.2)	
Large pelvic ROM (90th centile, >49°)	Number (%) of people with **large pelvic** flexion	10 (10%)	6 (6%)	NS
	Prevalence ratio	-	0.6 (0.2-1.5)	
Mean pelvic tilt ratio	Pelvic tilt range/range of trunk ROM change	2.1 ± 1.3	2.4 ± 1.4	NS
Small tilt ratio (10th centile, <0.69)	Number (%) of people with **small pelvic tilt** range	10 (10%)	6 (5.7%)	NS
	Prevalence ratio		0.58 (0.2-1.5)	

Large tilt ratio (>3.8)	Number (%) of people with **large pelvic** flexion	10 (10%)	13 (12%)	NS
	Prevalence ratio		1.27 (0.6-2.6)	
Mean relative sitting position	Max slump sit = 100%, maximum upright sit = 0%	48 ± 35%	50 ± 35%	NS
Slumped sitting (10th centile, > 89%)	Number (%) of people with **slumped sitting**	10 (10%)	16 (16%)	NS
	Prevalence ratio	-	1.7 (0.8-3.2)	
Upright sitting (90th centile, >12%)	Number (%) of people with **upright sitting**	10 (10%)	10 (10%)	NS
	Prevalence ratio	-	1.0 (0.4-2.2)	

* Adjusted prevalence ratio's considering the effect of age and sex are reported only, as there was minimal difference between unadjusted and adjusted ratios indicating minimal effect of age and sex

Table 5.5 Relationship of high pain score to kinematic parameters

Kinematic parameter	Total Number of LBP subjects with data	No. of LBP subjects with atypical movement	No. of LBP subjects with LOW PAIN score on bending/sitting	No. of LBP subjects with HIGH PAIN score on bending/sitting	Association with 'HIGH PAIN on bending/sitting' score
Flexion kinematic parameters					
Small Trunk ROM	**135**	**64**	27	37	NS
Large Trunk ROM	**135**	**4**	2	2	NS
Small Lumbar ROM*	**135**	**38**	12	26	p=.012
Large Lumbar ROM	**135**	**7**	2	5	NS
Small Pelvic ROM*	**135**	**44**	14	30	p=.011
Large Pelvic ROM	**135**	**6**	4	2	NS
Small LPC	**135**	**1**	9	8	NS
Large LPC	**135**	**16**	8	8	NS
Low FRR	**132**	**67**	33	34	NS
Pelvic delay at onset	**101**	**17**	10	7	NS
Lumbar delay at onset	**101**	**16**	10	6	NS
Pelvic delay at 20o	**96**	**28**	15	13	NS
Lumbar delay at 20o	**96**	**19**	10	6	NS
Slow trunk movement	**101**	**47**	26	21	NS
Sitting kinematic parameters					
Small Pelvic tilt range	**100**	**9**	6	3	NS
Large Pelvic tilt range	**100**	**6**	2	4	NS
Small tilt ratio	**100**	**5**	5	0	NS
Large tilt ratio	**100**	**12**	7	5	NS
Slumped sitting position	**100**	**17**	7	10	NS
Upright sitting position	**100**	**9**	5	4	NS

ROM = range of motion, FRR = flexion relaxation response, LPC = lumbo-pelvic co-ordination, NS= nonsignificant

* Significant difference noted in yellow with greater frequency of people reporting higher pain scores.

5.4.5.   Discussion

This exploratory study measured flexion (in standing) and sitting lumbo-pelvic kinematic parameters, in typical clinical settings, using wearable wireless inertial motion sensors in people with and without LBP. We examined between-group differences, defined and calculated the prevalence of 'atypical' flexion and sitting kinematic parameters for each group, and tested the relationship between 'high pain' scores and atypical movement. Between group differences showed less trunk, lumbar and pelvic ROM, less flexion relaxation, delayed pelvic movement at the start of movement and slower trunk flexion for the LBP group. Using the 10th/90th centiles for people without LBP to establish atypical movement parameters, we found a significantly greater prevalence of small trunk, lumbar and pelvic ROM for the LBP group, but not for large trunk, lumbar or pelvic ROM. Similarly, there was a greater prevalence in the LBP group for less flexion relaxation, slow trunk movement and delayed timing of pelvic (versus lumbar) movement to achieve 20°. No between group differences were seen for lumbo-pelvic co-ordination or for any of the sitting parameters. For most atypical kinematic parameters, there was no relationship with high pain scores during flexion or sitting, with the exception of small lumbar and pelvic ROM being associated with a high score on pain on forward bending.

Defining atypical movement with a dichotomising approach

Previous studies have reported similar between-group differences for lower ROM (Laird, R et al., 2014), slower movement velocity (Laird, R et al., 2014; Marras, WS et al., 1993a; Marras, WS et al., 1986) and less flexion relaxation (Geisser, ME et al., 2005) in those with LBP. We used the term 'atypical' rather than dysfunctional or abnormal movement because movements that are atypical were present in both groups. Defining atypical movement and dichotomizing the data, allowed testing of the prevalence of both low **and** high values for each parameter. This was useful because both the LBP and NoLBP groups included people with atypically small **and** large values for all parameters. The presence of atypical movement in people without a history of significant LBP suggests that these parameters may pre-exist pain. However, the significantly higher prevalence of atypically small ROM, less flexion relaxation, longer movement duration and delayed pelvic movement, suggests a relationship with pain. The nature of this relationship, whether causative or a consequence of pain, is unclear.

We chose a dichotomizing approach because it reflects decision making used in clinical practice and has potential utility in determining which movement components might be a target of therapeutic intervention. The use of 10th centile criterion was an arbitrary decision, based partially on a consideration of our sample size. Larger centiles could have been chosen but, by definition, atypical movement would have been more common. Smaller centiles could also have been used but would have needed larger samples because of the smaller number of people classified as having atypical movement and the corresponding increase in the uncertainty of the statistical estimates.

As atypical movement is present in people who have never had LBP a potentially important question for future research would be to explore in longitudinal studies whether some atypical movements are prognostic indicators for the development of LBP in some people.

ROM

The results from our study indicate a significant relationship between the presence of LBP and small ROM, suggesting that identifying atypically low ROM maybe potentially important clinically. There is evidence of an association between pain-related fear, reduced ROM and poor flexion relaxation that is consistent with our data (Geisser, ME et al., 2004). Assessing spinal movement in people with LBP has been problematic with large variations in reported lumbar ROM, poor reliability arising from differing measuring techniques and devices, and conflicting reports about the utility of measuring spinal movements as a measure of activity limitation (Laird, R et al., 2014; Mayer, T et al., 1997; Miller, SA et al., 1992; Nitschke, J et al., 1999; Poitras, S et al., 2000; Zuberbier, O et al., 2001). Nevertheless, ROM remains a common feature of assessing and monitoring musculoskeletal injury, suggesting that measuring ROM is still considered to have clinical importance. People with acute LBP often demonstrate a reduced ROM that returns to 'normal' as pain reduces, suggesting pain as a cause of small ROM. However, the presence of small ROM in the NoLBP population indicates that small ROM is not only a response to injury or pain, but maybe present prior to pain occurring. This has implications for monitoring ROM as a 'response to change' variable. For a person who had small ROM prior to injury, improvements in pain or disability may not be similarly associated with changes in ROM associated with recovery compared to a person who, prior to injury, had a large ROM. This factor might partly account for the limited association reported between pain, activity limitation and ROM (Poitras, S et al., 2000). It would also be easy to think of the LBP group as 'restricted or stiffer' (smaller ROM) than the

NoLBP group, and while this appeared true for 48% of the LBP group, there was still considerable overlap with the NoLBP population. Indeed, some people with LBP have atypically high trunk, lumbar and/or pelvic ROM. While small ROM deficits are present in some people with LBP, they are not present in all LBP patients. So, interventions designed to improve or restore typical movement range are unlikely to be helpful if no, or minimal loss, of movement is present.

The concept of measuring both lumbar and pelvic ROM contributions to overall trunk flexion is not novel, however in a recent systematic review 10 out of 16 studies that measured flexion ROM only reported lumbar ROM (Laird, R et al., 2014). Functional activities that involve trunk flexion include lumbar and pelvic motion. Our results indicate that atypically small pelvic ROM is significantly more prevalent in the LBP group, suggesting that pelvic ROM should also be measured when examining trunk flexion. For example, when assessing a person with back pain, typical lumbar ROM may be present but accompanied by atypically small pelvic ROM.

Flexion relaxation and timing parameters

The absence of flexion relaxation has been repeatedly identified in people with LBP and improvements to pain have been associated with improved flexion relaxation following interventions specifically aimed at reducing muscle activation of lumbar extensor muscles in the fully flexed position (Marshall, Paul et al., 2006; Neblett, R et al., 2010; Neblett, R et al., 2014b). People with normal relaxation have a ratio near zero, so all ratio scores over 0.033 are atypically high ratio scores that indicate low/reduced flexion relaxation. Targeting people with LBP who have poor flexion relaxation is likely to be important, but not all people with LBP have poor flexion relaxation.

The clinical utility of the timing parameters measured with tools that can accurately measure movement over time is unclear. While it is biomechanically plausible that a relative delay or lag in pelvic or lumbar movement may have potential clinical implications by increasing biomechanical forces on upper or lower lumbar structures, there is currently no research evidence to support the clinical relevance of such findings. However, the observation that these delays exist and are more commonly seen in people with back pain suggests that they may have clinical relevance, but this requires further investigation. It is also plausible that slower movement velocity is a consequence of LBP and might be useful as a measure of change but there is no current evidence that slow movement may cause LBP.

Patterns of atypical movement

People with LBP are frequently considered to be heterogenous in a range of domains such as differing cognitive perspectives, trajectories of improvement, movement patterns and patho-anatomical diagnoses (Deyo, R et al., 2015; O'Sullivan, P et al., 2017; O'Sullivan, P. B., 2005; Sahrmann S., 2002). Our data demonstrates a wide spectrum for most kinematic parameters for both groups, highlighting the heterogenous nature of movement. In this sample, people with LBP could equally have high or a low percentage lumbar contribution (lumbo-pelvic co-ordination) to overall flexion, which represent different methods of achieving trunk flexion. Similarly, different patterns in movement timing were seen in 'onset-delay' i.e. in which region moves first. A pelvic delay (indicating lumbar spine moving first) was twice as prevalent in the LBP group, while a lumbar delay was seen equally in both groups. The relative time for pelvic and lumbar components to achieve 20° of flexion similarly reflected two different patterns of movement, where 29% of the LBP group had atypical, delayed pelvic movement and 18% had atypical lumbar delay. Overall, given the heterogeneity of these kinematic parameters, if a movement or position was associated with pain, and then targeted with a movement-based intervention, it is unlikely that a 'one-size fits all' approach will be helpful and that an individually targeted approach may be more likely to achieve better overall outcomes.

The relationship of pain to atypical flexion and sitting parameters

Evidence for a relationship between pain and movement has been unclear. We expected that high pain on bending or sitting might have been associated with corresponding atypical kinematic parameters at either end of the spectrum (high or low values). Our results did support a relationship between 'high-pain-on-bending' scores with small lumbar and pelvic ROM, consistent with other studies (Alschuler, KN et al., 2009; Geisser, ME et al., 2004; Wong, TK et al., 2004) but not with other flexion-related parameters. There was no significant relationship between 'high-pain-on sitting' scores and any sitting kinematic parameters. Given that sitting is frequently listed as an aggravating activity in people with LBP and that sitting postures are thought to be associated with LBP (O'Sullivan, K et al., 2012) it would be reasonable to think that atypical end-range sitting postures might be associated with higher levels of pain, however this was not seen in this sample. People with LBP sat with large variation in position with 16% sitting in atypically slumped and 10% in an atypically upright position. There is some evidence that bio-feedback to modify end-range sitting positions reduces LBP (Kent, P et al., 2015b) however further research is required to clarify the relationship of movement change to pain reduction.

The absence of a clear and consistent relationship between pain intensity and atypical movement might occur because pain is a multifactorial experience with numerous cognitive (Carroll, LJ et al., 2004; Zale, E et al., 2013), physiological and mechanical components, and does not necessarily have a linear correlation to activity limitation or participation restriction (Turner, JA et al., 2004). While it could be argued that pain may not be related to atypical movement, a number of trials of treatments that aim to modify movement in people with chronic LBP have shown improvements to pain and activity limitation (Fersum, KV et al., 2012; Kent, P et al., 2015b; Long, A et al., 2004). What is not known, but would be very useful to know, is whether those improvements in pain and activity limitation were mediated by changes in movement, or whether movement interventions improved those outcomes via other effects, such as increasing a sense of self efficacy or changing pain cognitions.

Strengths

While numerous studies have reported lumbosacral ROM, this paper is different in that it dichotomizes movement into typical and atypical values. It highlights the utility of capturing a number of 'high definition' kinematic parameters that include regional movement, timing, sequence patterns and electrical activity, and defining atypical movement. Because data for both NoLBP and LBP groups was taken from a number of clinics and geographic locations, it is likely that data is representative of both groups, increasing the validity of generalising these results to the broader population. The sample size was relatively large for a kinematic study and therefore it is more likely that less commonly seen variants would be included in this sample. The precision of the measurements is high, with accuracy levels reported by the manufacturer of $<1°$ for single plane movement and good concurrent validity ($<2°$) when comparing these wireless inertial sensors to other 'reference-standard' surface measurement systems (Charry, E et al., 2011; Ha, TH et al., 2012; Mjøsund HL et al., 2017). The reported data has clinical utility with the dichotomous approach reflecting aspects of clinical practice and the chosen kinematic parameters based on potentially clinically important movement characteristics.

Limitations

Skin surface measurement should be used cautiously as a representation of actual spinal movement, however it can be used to measure baseline and change characteristics, and to provide comparison

between typical and atypical movement. Using a skin surface measurement technique to measure movement has the advantage of being non-invasive and possible within a typical clinical setting. While skin movement can create artefact, flexion is less exposed to this risk than other movements such as extension (Laird, R et al., 2016).

Sitting kinematics recorded as 'usual, slumped and upright' may not reflect real world sitting practice. The nature of real-world sitting, such as sitting in a car, or on the participant's usual chair may alter the intensity or frequency of pain, as parameters of duration and sitting frequency were not explored in this study and are potentially important.

Higher prevalence rates of some atypical movement parameters may indicate an association with back pain, but low prevalence rates do not necessarily imply no relationship. It may be that some parameters such as high ROM are rarer but are still related to back pain.

This study examines univariate relationships only. It is possible that multivariate relationships (patterns or clusters) may exist where variables combine in clinically relevant groups. Further research will examine these possibilities. Theoretically, it is feasible that there are subgroups of people with relatively mutually-exclusive clusters or patterns of atypical movement that relate to other dimension of LBP, such as pain or activity limitation. Future research could also include other physiological movements such extension, lateral flexion and rotation but were omitted from this paper to reduce complexity, and to allow a focus on exploring and developing atypical movement definitions.

5.4.6.   Conclusion

This exploratory, cross-sectional study used wireless inertial and EMG sensors to measure lumbo-pelvic kinematics during trunk flexion and sitting position (ROM, timing, sequence coordination, relative sitting position, pelvic tilt range and extensor muscle activation) in a sample of NoLBP and LBP subjects. For flexion, significant mean differences were seen with the LBP group demonstrating lower ROM, less flexion relaxation, a greater delay of pelvic movement at the onset of trunk movement and slower trunk flexion. Atypical movement was defined based on the 10th/90th centiles of the NoLBP group. People in the LBP group had a significantly greater prevalence of small trunk, lumbar and pelvic ROM, reduced FRR, slow trunk movement and delayed timing of pelvic (versus lumbar) movement to achieve 20° of angular inclination. No between group differences or prevalence rates were seen for large ROM, lumbo-

pelvic co-ordination or for any of the sitting parameters. There was a relationship with high pain scores during flexion or on small lumbar and pelvic ROM but not with other flexion or any sitting atypical movement parameters. Some observed differences in lumbo-pelvic kinematic parameters for those with and without LBP appear both clinically relevant and biologically plausible.

Abbreviations

LBP = Low Back Pain

NoLBP = participants without low back pain

RMDQ = Roland Morris Disability Questionnaire

ROM = ROM

FRR = Flexion relaxation response

Declarations

Ethics approval and consent to participate

This research project was performed in accordance with the declaration of Helsinki with approval obtained from Monash University Human Research Ethics Committee (approval number CF12/1995-20 12001090, 2016-1100) and The Regional Committees on Health Research Ethics for Southern Denmark (approval number S-20110071). All participants gave written informed consent for testing and use of de-identified data, through the use of an ethics committee approved patient information and consent form.

Consent for publication

All participants were provided with a Monash University Human Research Ethics Committee approved patient information and consent form, which included consent for publication. All participants provided signed consent forms before being admitted into the study.

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to the data being used for further research in a current PhD project, but are available from the corresponding author on reasonable request. All raw data and information related to additional files can be obtained from the first author at robert.laird@monash.edu.

Competing interests

No benefits in any form have been, or will be, received for this study from a commercial party related directly or indirectly to the subject of this paper. This paper does not contain information about drugs. The authors do not hold stocks or shares in any company that might be directly or indirectly affected by this study. No patents have been applied for or received due to the content of this paper and there are no non-financial competing interests associated with this paper. The lead author (RL) has been engaged as a consultant by DorsaVi for training clinicians in how to use the ViMove device but otherwise has no financial interest in the company, DorsaVi, nor has received any funding for this study. DorsaVi has a 25% ownership in a private physiotherapy clinic that RL is a director of. PK has received a market-rate consulting fee from DorsaVi for clinical trial design advice unrelated to the current study but otherwise has no financial interest in the company, DorsaVi.

Funding

Authors' contributions

RL contributed to data collection. RL was the main author of this paper, with concept, writing, data analysis, interpretation, draft revision and gave approval of the final manuscript. PL contributed to data collection, data analysis, data cleaning, draft revision and approval of the final manuscript. JK provided concept guidance, statistical direction, analysis, draft revision and gave approval of the final manuscript. PK provided concept guidance, statistical analysis, draft revision and gave approval of the final manuscript. KU contributed to data contribution, data analysis, draft revision and approval of the final manuscript. RL, KU, PL, JK and PK agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Acknowledgements

5.4.7.   Bibliography for Laird et al (2018A)

Abboud, J., Nougarou, F., Page, I., Cantin, V., Massicote, D., & Descarreaux, M. (2014). Trunk motor variability in patients with non-specific chronic low back pain. *European Journal of Applied Physiology*.

Ahern, D. K., Follick, M. J., Council, J. R., Laser-Wolston, N., & Litchman, H. (1988). Comparison of lumbar paravertebral EMG patterns in chronic low back pain patients and non-patient controls. *Pain, 34*(2), 153-160.

Alschuler, K. N., Neblett, R., Wiggert, E., Haig, A. J., Geisser, M. E., Alschuler, K. N., et al. (2009). Flexion-relaxation and clinical features associated with chronic low back pain: A comparison of different methods of quantifying flexion-relaxation. *Clinical Journal of Pain, 25*(9), 760-766.

Carroll, L. J., Cassidy, J. D., & Cote, P. (2004). Depression as a risk factor for onset of an episode of troublesome neck and low back pain. *Pain, 107*(1-2), 134-139.

Charry, E., Umer, M., & Taylor, S. (2011). Design and validation of an ambulatory inertial system for 3-D measurements of low back movements. *Proceedings of Seventh International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP 2011) IEEE Conference Publications (http://ieeexplore.ieee.org/document/6146618/)*.

Deyo, R., Bryan, M., Comstock, B., Turner, J., Heagerty, P., Friedly, J., et al. (2015). Trajectories of Symptoms and Function in Older Adults With Low Back Disorders. *Spine, 40*(17), 1352-1362.

Fersum, K. V., O'Sullivan, P., Skouen, J. S., Smith, A., & Kvale, A. (2012). Efficacy of classification-based cognitive functional therapy in patients with non-specific chronic low back pain: A randomized controlled trial. *European Journal of Pain, 17*(6), 916-928.

Floyd, W., & Silver, P. (1951). The function of the erectores spinae muscles in flexion of the trunk. *Lancet, 6647*, 123-133.

Geisser, M. E., Haig, A. J., Wallbom, A. S., Wiggert, E. A., Geisser, M. E., Haig, A. J., et al. (2004). Pain-related fear, lumbar flexion, and dynamic EMG among persons with chronic musculoskeletal low back pain. *Clinical Journal of Pain, 20*(2), 61-69.

Geisser, M. E., Ranavaya, M., Haig, A. J., Roth, R. S., Zucker, R., Ambroz, C., et al. (2005). A meta-analytic review of surface electromyography among persons with low back pain and normal, healthy controls. *Journal of Pain, 6*(11), 711-726.

Grenier, S. G., & McGill, S. M. (2008). When exposed to challenged ventilation, those with a history of LBP increase spine stability relatively more than healthy individuals. *Clin. Biomech., 23*(9), 1105-1111.

Grimstone, S. K., & Hodges, P. W. (2003). Impaired postural compensation for respiration in people with recurrent low back pain. *Experimental Brain Research, 151*(2), 218-224.

Ha, T. H., Saber-Sheikh, K., Moore, A. P., & Jones, M. P. (2012). Measurement of lumbar spine range of movement and coupled motion using inertial sensors - A protocol validity study. *Manual Therapy*.

Hides, J., Gilmore, C., Stanton, W., & Bohlscheid, E. (2008). Multifidus size and symmetry among chronic LBP and healthy asymptomatic subjects. *Manual Therapy, 13*(1), 43-49.

Hodges, P., & Richardson, C. (1996). Inefficient muscular stabilization of the lumbar spine associated with low back pain: a motor control evaluation of transversus abdominus. *Spine, 21*(22), 2640-2650.

Hodges, P., van den Horn, W., Dawson, A., & Cholewicki, J. (2009). Changes in the mechanical properties of the trunk in low back pain may be associated with recurrence. *Journal of Biomechanics, 42*(1), 61-66.

Hodges, P. W., Coppieters, M. W., MacDonald, D., & Cholewicki, J. (2013). New insight into motor adaptation to pain revealed by a combination of modelling and empirical approaches. *European Journal of Pain, 17*(8), 1138-1146.

Intolo, P., Milosavljevic, S., Baxter, D. G., Carman, A. B., Pal, P., Munn, J., et al. (2009). The effect of age on lumbar range of motion: a systematic review. *Manual Therapy, 14*(6), 596-604.

Kell, R. T., Bhambhani, Y., Kell, R. T., & Bhambhani, Y. (2006). In vivo erector spinae muscle blood volume and oxygenation measures during repetitive incremental lifting and lowering in chronic low back pain participants. *Spine, 31*(22), 2630-2637.

Kent, P., Laird, R., & Haines, T. (2015a). The effect of changing movement and posture using motion-sensor biofeedback, versus guidelines-based care, on the clinical outcomes of people with sub-acute or chronic low back pain-a multicentre, cluster-randomised, placebo-controlled, pilot trial. *BMC Musculoskeletal Disorders*(16), 131-150.

Kent, P., Laird, R., & Haines, T. (2015b). The effect of changing movement and posture using motion-sensor biofeedback, versus guidelines-based care, on the clinical outcomes of people with sub-acute or chronic low back pain-a multicentre, cluster-randomised, placebo-controlled, pilot trial *BMC Musculoskeletal Disorders, 16*, 131-150.

Kent, P. P., & Lauridsen, H. H. P. (2011). Managing Missing Scores on the Roland Morris Disability Questionnaire. *Spine, 36*(22), 1878-1884.

Kim, M.-h., Yi, C.-h., Kwon, O.-y., Cho, S.-h., Cynn, H.-s., Kim, Y.-h., et al. (2013). Comparison of Lumbopelvic Rhythm and Flexion-Relaxation Response Between 2 Different Low Back Pain Subtypes. *Spine, 38*(15), 1260-1267.

Laird, R., Gilbert, J., Kent, P., & Keating, J. (2014). Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis. *BMC Musculoskeletal Disorders, 15*(1), 229.

Laird, R., Kent, P., & Keating, J. (2016). How consistent are lordosis, range of movement and lumbo-pelvic rhythm in people with and without back pain? *BMC Musculoskeletal Disorders*(17), 403-417.

Lamberg, E. M., & Hagins, M. (2012). The effects of low back pain on natural breath control during a lowering task. *European Journal of Applied Physiology, 112*(10), 3519-3524.

Lee, A. S., Cholewicki, J., Reeves, N. P., Zazulak, B. T., & Mysliwiec, L. W. (2010). Comparison of Trunk Proprioception Between Patients With Low Back Pain and Healthy Controls. *Archives of Physical Medicine and Rehabilitation, 91*(9), 1327-1331.

Long, A., Donelson, R., & Fung, T. (2004). Does it matter which exercise? A randomized control trial of exercise for low back pain. *Spine, 29*(23), 2593-2602.

Marras, W. S., Parnianpour, M., Ferguson, S. A., & al, e. (1993). Quantification and classification low back disorders based on trunk motion. *Eur J Phys Med, 3*, 218-235.

Marras, W. S., & Wongsam, P. E. (1986). Flexibility and velocity of the normal and impaired lumbar spine. *Archives of Physical Medicine & Rehabilitation, 67*(4), 213-217.

Marshall, P., & Murphy, B. (2006). Changes in the flexion relaxation response following an exercise intervention. *Spine, 31*(23), E877-883.

Mayer, T., Kondraske, G., Beals, S., & Gatchel, R. (1997). Spinal range of motion. Accuracy and sources of error with inclinometric measurement. *Spine, 22*, 1976-1984.

Miller, S. A., Mayer, T., Cox, R., & Gatchel, R. J. (1992). Reliability problems associated with the modified schober technique for true lumbar flexion measurement. *Spine, 17*(3), 345-348.

Mjøsund HL, Boyle E, Kjaer P, Mieritx RM, Skallgard T, & P., K. (2017). Clinically acceptable agreement between the ViMove wireless motion sensor system and the Vicon motion capture system when measuring lumbar region inclination motion in the sagittal and coronal planes. . *BMC Musculoskeletal Disorders, 18*(124).

Moseley, G. L., & Hodges, P. W. (2006). Reduced variability of postural strategy prevents normalization of motor changes induced by back pain: A risk factor for chronic trouble? *Behavioral Neuroscience, 120*(2), 474-476.

Neblett, R., Mayer, T. G., Brede, E., & Gatchel, R. J. (2010). Correcting abnormal flexion-relaxation in chronic lumbar pain: responsiveness to a new biofeedback training protocol. *Clinical Journal of Pain, 26*(5), 403-409.

Neblett, R., Mayer, T. G., Brede, E., & Gatchel, R. J. (2014a). The effect of prior lumbar surgeries on the flexion relaxation phenomenon and its responsiveness to rehabilitative treatment. *The Spine Journal, 14*, 892-902.

Neblett, R., Mayer, T. G., Brede, E., & Gatchel, R. J. (2014b). The effect of prior lumbar surgeries on the flexion relaxation phenomenon and its responsiveness to rehabilitative treatment. *Spine Journal: Official Journal of the North American Spine Society, 14*(6), 892-902.

Neblett, R., Mayer, T. G., Gatchel, R. J., Keeley, J., Proctor, T., Anagnostis, C., et al. (2003). Quantifying the lumbar flexion-relaxation phenomenon: theory, normative data, and clinical applications. *Spine, 28*(13), 1435-1446.

Nelson-Wong, E., Brendon, A., Csepe, D., Lancaster, D., & Callaghan, J. P. (2012). Altered muscle recruitment during extension from trunk flexion in low back pain developers. *Clinical Biomechanics, 27*, 994-998.

Nelson-Wong, E., & Callaghan, J. (2014). Transient Low Back Pain Development During Standing Predicts Future Clinical Low Back Pain in Previously Asymptomatic Individuals. *Spine, 39*(6), E379-E383.

Newcomer, K. L., Laskowski, E. R., Yu, B., Johnson, J. C., & An, K. N. (2000). Differences in repositioning error among patients with low back pain compared with control subjects. *Spine, 25*(19), 2488-2493.

Nitschke, J., Nattrass, C., Disler, P., Chou, M., & Ooi, K. (1999). Reliability of the American Medical Association Guides' Model for measuring spinal range of motion: its implication for whole-person impairment rating. *Spine, 24*(3), 262-268.

O'Connell, G. D., Vresilovic, E. J., & Elliott, D. M. (2011). Human intervertebral disc internal strain in compression: The effect of disc region, loading position, and degeneration. *Journal of Orthopaedic Research, 29*(4), 547-555.

O'Sullivan, K., O'Sullivan, P., O'Sullivan, L., & Dankaerts, W. (2012). What do physiotherapists consider to be the best sitting spinal posture? *Manual Therapy, 17*(5), 432-437.

O'Sullivan, P., Smith, A., Beales, D., & Straker, L. (2017). Understanding Adolescent Low Back Pain From a Multidimensional Perspective: Implications for Management. *Journal of Orthopaedic & Sports Physical Therapy, 47*(10), 741-751.

O'Sullivan, P. B. (2005). Diagnosis and classification of chronic low backpain disorders: Maladaptive movement and motor control impairments as underlying mechanism. *Manual Therapy, 10*, 242-255.

O'Sullivan, P. B., Burnett, A., Floyd, A. N., Gadsdon, K., Logiudice, J., Miller, D., et al. (2003). Lumbar repositioning deficit in a specific low back pain population. *Spine, 28*(10), 1074-1079.

Poitras, S., Loisel, P., Prince, F., & Lemaire, J. (2000). Disability measurement in persons with back pain: a validity study of spinal range of motion and velocity. *Archives of Physical Medicine & Rehabilitation, 81*(10), 1394-1400.

Pranata, A., Perraton, L., El-Ansary, D., Clark, R., Fortin, K., Dettmen, T., et al. (2017). Lumbar extensor muscle force control is associated with disability in people with chronic low back pain. *Clinical Biomechanics, 46*, 46-51.

Roland, M., & Fairbank, J. (2000). The Roland-Morris Disability Questionnaire and the Oswestry Disability Questionnaire. *Spine, 25*(24), 3115-3124.

Ronchi, A., Lech, M., Taylor, N., & Cosic, I. (2008). A reliability study of the new Back Strain Monitor based on clinical trials. *Conf Proc IEEE Eng Med Biol Soc. 693-6*, 693-696.

Ross, R., & LaStayo, P. (1997). Clinical Assessment of Pain. In van Deusen J & B. D (Eds.), *Assessment in Occupational Therapy and Physical Therapy*. Philadelphia: WB Saunders Co.

Sahrmann S. (2002). Movement impairment syndromes of the lumbar spine.In: Diagnosis and treatment of movement impairment syndromes. *Diagnosis and treatment of movement impairment syndromes.* (1st ed., pp. 5-118). St. Loius: Mosby Inc.

Seay, J. F., E.A, & Hamill, J. (2011). Low back pain status affects pelvis-trunk coordination and variability during walking and running. *Clinical Biomechanics, 26*(6), 572-578.

Steele, J., Bruce-Low, S., & Smith, D. (2014). A reappraisal of the deconditioning hypothesis in low back pain: review of evidence from a triumvirate of research methods on specific lumbar extensor deconditioning. *Current Medical Research and Opinion, 30*(5), 865-911.

Turner, J. A., Franklin, G., Heagerty, P. J., Wu, R., Egan, K., Fulton-Kehoe, D., et al. (2004). The association between pain and disability. *Pain, 112*(3), 307-314.

Villumsen, M., Madeleine, P., Jorgensen, M., Holtermann, A., & Samani, A. (2016). The variability of the trunk forward bending in standing activities during work vs. leisure time. *Applied Ergonomics, 58*, 273-280.

Watson, P., Booker, C., Main, C., & Chen, A. (1997). Surface electromyography in the identification of chronic low back pain patients: the development of the flexion relaxation ratio. *Clinical Biomechanics, 12*, 165-171.

Wong, T. K., Lee, R. Y., Wong, T. K. T., & Lee, R. Y. W. (2004). Effects of low back pain on the relationship between the movements of the lumbar spine and hip. *Human Movement Science, 23*(1), 21-34.

Zale, E., Lange, K., Fields, S., & Ditre, J. (2013). The relation between pain-related fear and disability: A metaanalysis. *Journal of Pain, 14*(10), 1019-1030.

Zuberbier, O., Kozlowski, A., Hunt, D., Berkowitz, J., Schultz, I., Crook, J., et al. (2001). Analysis of the convergent and discriminant validity of published lumbar flexion, extension, and lateral flexion scores. *Spine, 26*(20), E472-478.

5.5.   Summary of results

The study reported in Laird et al. (2018A) defined atypical flexion and sitting lumbo-pelvic kinematic parameters that are of potential clinical interest and calculated the prevalence of these atypical parameters in 266 people with and without persistent LBP. Differences in movement were seen between the two groups. Small trunk, lumbar and pelvic ROM, delayed pelvic movement (compared to lumbar movement), a loss of FRR and slower movement speed were all significantly more common in people with persistent LBP. This significantly greater prevalence of atypical movement confirms that the relationship between movement and LBP warrants further investigation.

5.6.   Defining atypical movement

Defining atypical movement has some advantages but requires decisions that are necessarily arbitrary. A simple perspective of movement would be to consider that as a movement deficit increased, pain intensity would correspondingly increase. However, no discernible, consistent association between lumbo-pelvic kinematic parameters and either pain or activity limitation was seen in Laird et al. (2018A). Figure 5.5 graphically displays correlations between lumbo-pelvic kinematic parameters, activity limitation and pain. Other trials that focus on lumbar ROM have also reported little or no correlation between ROM and pain/activity limitation (Nattrass, CL et al., 1999; Parks, KA et al., 2003; Poitras, S et al., 2000; Sullivan, MS et al., 2000).

An alternate view could be that a deficit may have to reach a threshold level before it has any relationship to pain or activity limitation. This view is reflected in common clinical practice, where clinicians attempt to differentiate between typical and atypical movement, posture or function. If movement can be quantified, a movement parameter might be identifiable as potentially relevant/important once it reaches a certain threshold. The decision to use the 10th/90th centiles of the NoLBP group as cut-points that dichotomise people into typical and atypical movement was arbitrary. As noted in Laird et a. (2018A), alternative cut-point values could have been investigated, however smaller centiles (i.e. 5th and 95th centiles) would require much larger samples to satisfy statistical requirements, while larger centiles would result in a greater frequency of movements classified as 'atypical'. The choice to use 10th/90th centiles balanced the requirements of sample size and statistical rigour with a pragmatic clinically-based estimate of what might represent atypical movement.

However, before clinicians could confidently use cut-points from Laird et al. (2018A) to identify atypical lumbo-pelvic kinematic parameters, replication studies using the same device and method (10th and 90th centiles) could help to establish whether similar values for cut-points are found in other samples. Cut-points are also likely to be slightly affected by age and sex (Bible, JE et al., 2008; Intolo, P et al., 2009; Troke, M et al., 2001) and some lumbo-pelvic kinematic parameters such as lordosis may have ethnically specific values (Been, E et al., 2014; Trudelle-Jackson, E et al., 2010).

Figure 5.5 Scatterplot correlations between lumbo-pelvic kinematic parameters with pain and activity limitation
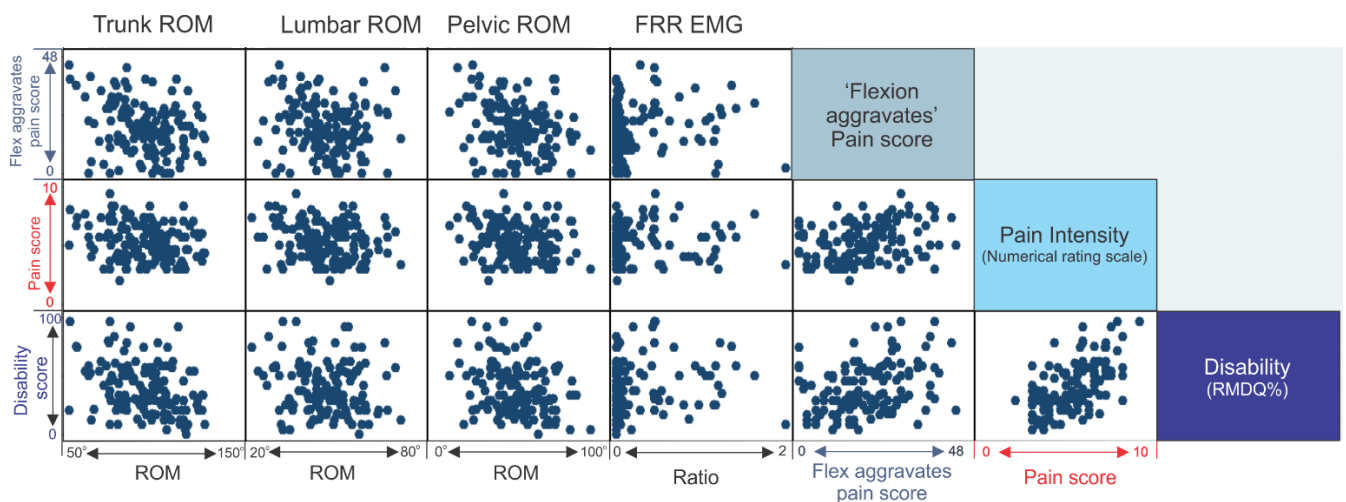
Figure 5.5 compares lumbo-pelvic kinematic parameters with pain or activity limitation. The stronger the correlation, the dots (which represent each individual and the relationship between two parameters) will more align along an ascending or descending line. Legend: Trunk ROM (peak T12 angular inclination), Lumbar ROM, Pelvic ROM (peak S2 angular inclination), FRR EMG = ratio of electrical activity of extensor muscles, also known as an FRR ratio.

5.7. People with persistent LBP have differing atypical movement parameters

Although there is a greater prevalence of atypical lumbo-pelvic kinematic parameters in people with persistent LBP, compared with people with no LBP, not all people with persistent LBP have the same atypical movements. The prevalence rate for each lumbo-pelvic kinematic parameter can be initially summarised at a whole LBP

group level, and this is shown below in Table 5.6, as reported in Laird et al. (2018A). Clearly, some atypical

parameters appear much more prevalent than others.

Table 5.6 Prevalence rates of atypical flexion-related lumbo-pelvic kinematic parameters

Range of Motion	Prevalence rate
Small trunk ROM (10th centile, <93°)	48%
Large trunk ROM (90th centile, >128°)	3%
Small lumbar ROM (10th centile, <39°)	29%
Large lumbar ROM (90th centile, >65°)	6%
Small pelvic ROM (10th centile, <42°)	34%
Large pelvic ROM (90th centile, >75°)	5%
Lumbo-pelvic co-ordination	
Small Lumbar contribution (10th centile, <38%)	14%
Large Lumbar contribution (90th centile, >63%)	13%
FRR	
Low FRR (10th centile, >0.033 for a ratio of EMG activity)	52%
Delay at 0°	
Pelvic delay at onset of movement (10th centile, >0.53sec)	18%
Lumbar delay at onset of movement (90th centile, >0sec)	10%
Delay at 20°	
Pelvic delay at 20° of trunk flexion (10th centile, >0.81sec	29%
Lumbar delay (90th centile, >0.15sec)	18%
Mean movement duration	
Slow Trunk movement (10th centile, >3.12 seconds)	47%

Although the findings from this thesis only focussed on flexion-related lumbo-pelvic kinematic parameters, it is

likely that other movement-related deficits may also be seen in some people with LBP. While replication studies

are required to confirm or clarify the frequency of atypical lumbo-pelvic kinematic parameters (or other

movement-related parameters) in the general population, the findings from Laird et al. (2018A) provide some

indication of which lumbo-pelvic kinematic parameters are more commonly seen.

5.8.   ROM measurements

Laird et al. (2016) reported that **pelvic ROM was larger** for the LBP group (n=30) than the NoLBP group (n = 32), with no significant differences seen between groups for lumbar or trunk flexion ROM. In contrast, Laird et al. (2018A) found trunk, lumbar and **pelvic ROM were smaller** for the LBP group (n=140) than the NoLBP group (n=126), which is consistent with the results of the systematic review reported in Chapter 3 (Laird et al. (2014)). That review reported reduced flexion lumbar ROM for people with LBP when the included studies were pooled using meta-analysis (n=1,671). Two possible explanations for the different conclusions in the two papers could include (i) random sampling differences, or (ii) a local phenomenon related to the sample in Laird et al., 2016, where all the subjects came from one source. For example, perhaps all subjects had hamstring stretching as part of their intervention (compared with the multi-source sample seen in Laird et al. 2018A). However, whatever the source of difference, it highlights the following important concepts that underpin the analysis of ROM.

5.8.1.   Small lumbar ROM is infrequently seen

Lumbar ROM is a commonly chosen measure of physical performance but may have limited use because 'small lumbar ROM' seems to be present in a minority of people with persistent LBP. In the cohort reported in Laird et al. (2018A), only 29% of people with persistent LBP had a 'small lumbar ROM'. In this same sample, more people with persistent LBP had a small pelvic ROM (34%). If one were choosing to measure lumbo-pelvic kinematic parameters on the basis of prevalence, only using data from Laird et al. (2018A), then choosing lumbar flexion ROM measurement as an outcome measure, is less likely to be useful than choosing trunk or pelvic ROM, reduced FRR or speed of trunk movement. If lumbar ROM is chosen as an outcome measure, it may be that only those people with atypically lower lumbar ROM at baseline have potential to demonstrate significant change.

5.8.2.   Measuring ROM requires measurement of lumbar AND pelvic components

These findings also suggest that, both lumbar and pelvic contributions should be measured when testing if there are lumbo-pelvic movement differences between a NoLBP and an LBP group. A typical flexion activity, for example, bending to put shoes on, involves both lumbar and pelvic movement. If only lumbar movement is

measured, then an important source of potentially atypical movement may be overlooked. For instance, lumbar movement may have a typical ROM but the pelvic ROM may be atypically small. If the aim of a study were to test if people with LBP have a movement deficit, then measuring both lumbar and pelvic kinematic parameters would appear to be useful. Studies and reviews that indicate no differences in lumbar ROM between those with and without LBP without reference to pelvic contribution, particularly when referring to standing forward flexion, may provide an incomplete and potentially inaccurate comparison (i.e. suggesting no difference in movement range when a difference does exist but the component that was different was not measured). Without a full picture of lumbo-pelvic kinematic parameter differences between an LBP and a control group, understanding the nature and strength of any relationship between movement and pain or activity limitation will be under-informed.

5.9.   Atypical ROM as a risk factor

In this study of flexion-related lumbo-pelvic kinematic parameters, 10% of the **NoLBP** group were classified as having an atypically small ROM. The higher prevalence of small trunk, lumbar and pelvic ROM in the **LBP** group invites the question about whether small ROM in a NoLBP population might be a risk factor for future LBP. The review by Sadler et al. (2017) concluded a significant relationship between small lateral flexion ROM and increased risk of LBP development. This was based on a meta-analysis of three studies (see Figure 5c), although one study by Adams et al. (1999) represented 66% of all the pooled data. In that meta-analysis, a subset of student nurses (n=125) was analysed due to their relative homogeneity of age and occupation. In that sub-cohort, smaller flexion ROM was also significantly correlated with incidence of LBP occurrence in a 12-month period. Biomechanical studies report that end-range flexion under load increases the risk of intervertebral disc and endplate failure (Gallagher, S et al., 2005; Heeswijk, V et al., 2017; Rajasekaran, S et al., 2013). End-range movements of flexion and lateral flexion combined with loads create the greatest likelihood of disc failure (Berger-Roscher, N et al., 2016). It is biologically plausible that if an individual has a small ROM, the likelihood of engaging in end-range movement through normal activities of daily living is higher, and thus the risk of developing LBP may also be higher. Further research using a prospective design in large samples, would be useful to investigate whether small ROM is an important risk factor for the development of LBP.

5.10.   Sitting and pelvic tilt movement in sitting

Laird et al. (2018A) investigated three sitting parameters that relate to sitting posture and pelvic movement. Sitting has been implicated as an aggravating activity for people with LBP (Pengel, LH et al., 2004) and is thought to be associated with the development of LBP (McGill, S, 2016, p. 194). Biomechanical factors such as increased intradiscal pressure (Nachemson, A, 1981; Wilke, HJ et al., 1999) or end-range positioning of lumbar joints (e.g. slumped sitting) may have an association with pain. Laird et al. (2018A) characterised sitting position by attempting to describe the 'usual' sitting position relative to full slump and full upright sitting. The results did not show any difference between groups for frequency of slumped or upright sitting. There is considerable interest in investigating the biomechanics of sitting posture/position due to the frequent association of LBP with sitting (Castanharo, R et al., 2014; Claus, AP et al., 2009, 2016). For example, Claus et al (2018) compared the muscle activation patterns in sitting of 10 people with LBP with those of 14 people without LBP. They demonstrated that there were differences in muscle activation patterns seen in sitting between people with and without LBP, with greater activation of longissimus thoracic in a long lordotic posture (a functional lordotic sitting position involving extension through the lower thoracic and lumbar spine) being significantly higher in the LBP group. Dankaerts et al. (Dankaerts, W. et al., 2006a; Dankaerts, W. et al., 2006e) reported no difference in muscle activation patterns or sitting position during sitting comparing people with and without LBP. However, when the LBP group were sub-grouped into flexion control and 'active extension' control impairment subgroups, they found the flexion subgroup had a more kyphotic sitting posture compared with the extension subgroup that sat in a more lordotic position with greater activation of thoracolumbar extensor muscles when compared with the control group (p<.001).

In summary, although differences in muscle activation patterns and angle during sitting have been reported, Laird et al (2018A) did not find any between group differences in any measured atypical lumbo-pelvic kinematic sitting parameters.

5.11.   Exploring relationships between lumbo-pelvic kinematic parameters

In Laird et al. (2018A), univariate analysis was used to compare the prevalence rates for each parameter in those with and without LBP. Univariate analysis is commonly used in studies that investigate movement-related parameters. However, univariate comparisons do not indicate if there are relationships between parameters.

For instance, it is unknown if people who have small lumbar ROM always, frequently or infrequently also have small pelvic ROM. From a clinical perspective, if a clinician were to focus on a single element without considering other lumbo-pelvic kinematic or related features, an incomplete strategy for therapeutic intervention may result. One perspective is that each lumbo-pelvic kinematic parameter could be considered as an individual piece of a jigsaw puzzle. Some parts of the jigsaw puzzle may have a relationship with other pieces, and when joined together, provide a larger, more informative picture of movement. Or, it may be that each parameter is completely independent. The last study in this thesis explored whether there are multivariable relationships that define lumbo-pelvic kinematic patterns.

6. Chapter 6 Are there patterns within lumbo-pelvic kinematic parameters: univariate versus multivariable analysis

6.1. Univariate versus multivariable analysis

Movement-based classification systems (Karayannis, N et al., 2012) have been proposed that attempt to subgroup movement-based heterogeneity in people with persistent LBP. These systems use multiple pieces of information to classify people with persistent LBP into more homogenous clusters/subgroups of similar presentations, based on signs and symptoms (Fritz, J et al., 2003; Key, J, 2010; McKenzie, R et al., 2003a; O'Sullivan, P.B., 2005b; Petersen, T et al., 2003; Sahrmann, S, 2002a). No movement-based classification system uses quantified lumbo-pelvic kinematic parameters as part of its classification system.

Using multiple pieces of information to cluster people with persistent LBP into subgroups conceptually contrasts with kinematic studies that typically use univariate classical statistical methods to test for between group comparisons. Mean values for a single lumbo-pelvic kinematic parameter assist in understanding how far away from the mean an individual is on any given parameter but do not easily contribute to a potentially larger picture that may be formed by relationships between lumbo-pelvic kinematic parameters.

6.1.1. Latent class analysis

The study reported in Laird et al. (2018A) explored univariate relationships between lumbopelvic kinematic parameters and pain but did not test for relationships between lumbopelvic kinematic parameters or if clusters of lumbo-pelvic kinematic parameters might form subgroups. One approach to forming subgroups is to anchor the analysis from a particular outcome, such as pain intensity. Examples of such techniques include linear or logistic regression and, because these involve the use of a dependent variable, this approach is called 'supervised' analysis. Another approach that is increasingly used in health research subgrouping is called 'unsupervised' analysis because it examines inherent relationships between variables within the data set using an approach that is independent of an outcome measure. Unsupervised analysis attempts to maximize the homogeneity of multivariable scoring patterns within subgroups and maximize the heterogeneity between subgroups.

Latent class analysis is a statistical method that looks for relationships between observed variables from a sample and then describes if these relationships (patterns) vary across the individuals in the sample. The 'latent class' is the unseen, potential, categorical 'grouping' variable that results from that process.

Latent Class Analysis is a probabilistic form of unsupervised analysis that has a number of advantages compared to traditional forms of unsupervised cluster techniques. These include being able to use variables of mixed measurement types, to statistically evaluate the optimal number of subgroups, to handle missing data, to provide classification probabilities for each individual, to provide model-based parameters that can be used to classify new individuals not in the derivation sample, and to optimise classification accuracy (Bacher, J et al., 2004; Collins, L et al., 2010; Gelbard, R et al., 2007; Magidson, J et al., 2002). Based on simulation studies, a minimum of 200 participants for Latent Class Analysis with continuous variables is recommended (Nylund, K et al., 2007). This approach has been previously used in LBP research, for example, to examine if patterns of MRI findings relate to patho-anatomical pathways of degeneration (Jensen, Jensen et al. 2013), to test if patterns of LBP symptoms relate to isometric trunk strength and body sway (Paalanne, Korpelainen et al. 2008) and to look for patterns of recovery trajectories (Kongsted, Kent et al. 2015). When used in LBP research, these scoring patterns or clusters of related variables are often referred to as subgroups.

Latent class analysis attempts to find the best balance between considering every individual as a unique 'subgroup' at one end of the spectrum and considering all individuals belong to the same group at the other end of the spectrum. A key concept of latent class analysis is to determine the optimal number of subgroups (Kongsted and Nielsen 2017) by starting with a model consisting of one large group then adding subgroups (a two-subgroup model, a three-subgroup model, a four-subgroup model etc.). The best model is determined using a statistical measure of model performance (e.g. the Bayesian Information Criterion). Such statistical measures of model performance balance the amount of variance explained by the model with the complexity of the model. In this approach, the model with the least number of subgroups that explains the most variance is sought. Individuals within the sample are also assigned a posterior probability score of membership of each subgroup ('posterior' meaning taking into account the relevant evidence *after* testing for relationships between variables), where a score of 1 = 100% probability of belonging to a subgroup, i.e. the individual fits the pattern exactly. Latent class analysis is a relatively robust statistical process that can handle missing data and includes different types of data (dichotomous, ordinal, interval), without the need to scale or normalise variables (Magidson and

Vermunt 2002, Kongsted and Nielsen 2017). A brief description of latent class analysis is provided in the following study, (see section 6.2.3).

6.1.2. Testing if patterns of lumbo-pelvic kinematic parameters are present

The fifth and last paper (third empirical study) of this thesis explored relationships between lumbo-pelvic kinematic parameters. If relationships exist, then there may be potential to discern subgroups of people with clinically recognisable movement patterns and assess whether any of those patterns are associated with pain or activity limitation. This study has been submitted to BMC Musculoskeletal Disorders and is reproduced in the following section as submitted, complete with amendments following recent review. The study is referenced as:

Laird, R., Keating, J., & Kent, P. (2018B). There are subgroups of lumbo-pelvic flexion kinematics in people with and without back pain *BMC Musculoskeletal Disorders, Submitted*.

6.2. Subgroups of lumbo-pelvic flexion kinematics are present in people with and without persistent low back pain

Robert A Laird[1]

Email : robert.laird@monash.edu

Jennifer L Keating[1]

Email: jenny.keating@monash.edu

Peter Kent[2,3]

Email: peter.kent@curtin.edu.au

[1] Department of Physiotherapy, Monash University, PO Box 527, Frankston, Victoria 3199, Australia

[2] School of Physiotherapy and Exercise Science, Curtin University, Perth, Australia

[3] Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark

Postal Address:

[*] Corresponding author. Robert Laird, 380 Springvale Rd, Forest Hill, 3131 Melbourne, Victoria, Australia

6.2.1. Abstract

Background

Movement dysfunctions have been associated with persistent low back pain (LBP) but optimal treatment remains unclear. One possibility is that subgroups of persistent LBP patients have differing movement characteristics and therefore different responses to interventions. This study examined if there were patterns of flexion-related lumbo-pelvic kinematic and EMG parameters that might define subgroups of movement.

Methods

This was a cross-sectional, observational study of 126 people without any history of significant LBP and 140 people with persistent LBP (n=266). Wireless motion and surface EMG sensors collected lumbo-pelvic data on flexion parameters (range of motion (ROM) of trunk, lumbar, and pelvis), speed, sequence coordination and timing, and EMG extensor muscle activity in forward bending (flexion relaxation)), and sitting parameters (relative position, pelvic tilt range and tilt ratio). Latent class analysis was used to identify patterns in these parameters.

Results

Four subgroups with high probabilities of membership were found (mean 94.9%, SD10.1%). Subgroup 1 (n=133 people, 26% LBP) had the greatest range of trunk flexion, fastest movement, full flexion relaxation, and synchronous lumbar versus pelvic movement. Subgroup 2 (n=73, 71% LBP) had the greatest lumbar ROM, less flexion relaxation, and a 0.9 sec lag of pelvic movement. Subgroup 3 (n=41, 83% LBP) had the smallest lumbar ROM, a 0.6 sec delay of lumbar movement (compared to pelvic movement), and less flexion relaxation than subgroup 2. Subgroup 4 (n=19 people, 100% LBP) had the least flexion relaxation, slowest movement, greatest delay of pelvic movement and the smallest pelvic ROM. These patterns could be described as standard (subgroup 1), lumbar dominant (subgroup 2), pelvic dominant (subgroup 3) and guarded (subgroup 4). Significant post-hoc differences were seen between subgroups for most lumbo-pelvic kinematic and EMG parameters. There was greater direction-specific pain and activity limitation scores for subgroup 4 compared to other groups, and a greater percentage of people with leg pain in subgroups 2 and 4.

Conclusion

Four subgroups of lumbo-pelvic flexion kinematics were revealed with an unequal distribution among people with and without a history of persistent LBP. Such subgroups may have implications for which patients are likely to respond to movement-based interventions.

Subgroups of lumbo-pelvic flexion kinematics are present in people with and without persistent LBP

6.2.2. Introduction

Persistent low back pain (LBP) is often described as a multidimensional problem, within a bio-psycho-social context (Marin, TJ et al., 2017; Waddell, G, 1987). Dimensions that are thought to influence pain and function include patho-anatomic changes, cognitions and emotions, lifestyle, societal circumstances, and movement/posture (Delitto, A et al., 1995; Deyo, R et al., 2015; Kongsted, A et al., 2012; Kongsted, A et al., 2015; O'Sullivan, P et al., 2017; O'Sullivan, P. B., 2005; Sahrmann S., 2002). People with LBP are quite heterogeneous within these dimensions. Identifying clinically important subgroups that are relatively homogenous within these dimensions has been a research priority (Borkan, JMMDP et al., 1998; Costa, L et al., 2013), based on a prevailing belief that better outcomes are likely when treatment is matched with subgroup-specific features.

A number of movement-based classification systems have been developed, underpinned by observations of relationships between movement and LBP, with the intention of providing subgroup-specific, targeted treatment (Delitto, A et al., 1995; Hodges, P et al., 2013; McKenzie, R et al., 2003a; O'Sullivan, P.B., 2005b; Sahrmann, S, 2002a). Different classification systems use different, albeit overlapping, combinations of examination findings to define subgroups, (Karayannis, N et al., 2012). Examination findings include subjective reports, visual observation and pain responses to movement, but rarely include measurement of lumbo-pelvic kinematic parameters.

There is evidence that flexion-related activities are particularly important in LBP. For example, in a study on people with subacute LBP by Pengel et al (2004), the three most frequently nominated pain-related activities were sitting, bending and lifting, which all involve elements of flexion. As a consequence, there are potentially important clinical questions to be investigated in empirical measurements of flexion-related lumbo-pelvic kinematics: (i) are there different patterns in the way people perform flexion, and (ii) are any patterns more common in people with persistent LBP than in people who have never had LBP?

Studies of lumbo-pelvic kinematic parameters have identified differences in range of motion (ROM) in people with and without LBP, using between-group mean differences and their standard deviations

(SD), but have generally not described subgroups based on lumbo-pelvic kinematics (Laird, R et al., 2014; Marras, WS et al., 1999b). Identifying that lumbar ROM is, on average, reduced in people with LBP (Laird, R et al., 2014) would suggest that improving ROM might be a treatment target. However, if some people with LBP do not have reduced lumbar ROM, a treatment strategy aimed at increasing lumbar ROM may be unhelpful. Lumbo-pelvic kinematics include a range of parameters such as trunk, lumbar and pelvic ROM, timing of regional movement, muscle activation, movement duration, movement coordination, and postural position. Using multivariable clusters of these kinematic parameters may identify different patterns of flexion that might assist in matching targeted interventions to specific lumbo-pelvic kinematic goals.

Previous work by Marras et al (1995b), Dankaerts et al (2009) and Mayer et al (2009) all used kinematic analysis to validate pre-defined subgroups of people with persistent LBP but did not use kinematic data a priori to define subgroups. Marras et al (1995b) quantified and matched angular data, velocity and acceleration kinematic parameters to modified Quebec classification subgroups. Dankaerts et al (2009) measured ROM and EMG parameters in two subgroups of people classified with an O'Sullivan classification system (O'Sullivan, P.B., 2005b) and Mayer et al (2009) pre-classified people with persistent LBP into four groups based on 'normal' versus 'abnormal' lumbo-pelvic ROM and EMG of lumbar extensors during flexion.

The availability of wireless inertial and EMG sensors for use in clinical environments now enables detailed and accurate measurement of lumbo-pelvic movement. A recent study (Laird et al, 2018) on lumbo-pelvic kinematics using data from this type of device found that, compared to people without LBP, people with persistent LBP showed a higher prevalence of smaller trunk, lumbar and pelvic ROM, slower movement, delayed pelvic versus lumbar movement and greater lumbar extensor muscle activation in the fully flexed position. That study also identified a wide range of variance for most parameters. It did not, however, investigate whether subgroups of movement patterns were evident in the data.

The current study aimed to explore (i) if patterns (subgroups) of flexion-related lumbo-pelvic kinematics could be identified in a suitably large sample of people, (ii) if patterns were present, whether they occurred with different frequency in people with and without persistent LBP, and (iii) to investigate clinical and demographic characteristics that are associated with any patterns.

6.2.3.   Method

This cross-sectional, observational study used latent class analysis to identify subgroups in the movement patterns of flexion-related lumbo-pelvic kinematics using a previously reported dataset (Laird et al 2018).

Study sample

Inclusion and exclusion criteria have been previously reported in detail (Laird, R et al., 2016). In summary, 140 adults (18-65 years old) with persistent LBP were recruited from primary and secondary care (physiotherapy clinics and outpatient departments). Inclusion criteria were LBP>3 months' duration, pain scores of 3 or higher (on a 0-10 point numerical rating scale), with current back +/- leg pain. Exclusion criteria were previous lumbar surgery; any invasive spinal procedures for LBP, including therapeutic injections, within the last 12 months; any serious medical or musculoskeletal issues that had the potential to affect the lumbo-pelvic region; an implanted electrical medical device; a BMI > 30 (where it becomes difficult to palpate bony landmarks); or pregnancy. Adults (n=126) who had never had LBP (NoLBP group) were recruited from universities, workplaces and community groups by poster and word of mouth advertising and were eligible for inclusion if they had no significant health issues that would affect movement, and no history of any LBP episode that required visiting a health professional or taking time off either work or usual sport. All participants were screened for inclusion and exclusion initially by administrative staff and then re-checked by the assessing clinician. In addition, people in the NoLBP group were asked if they had any current LBP and excluded if they did. Demographic data can be seen in Table 1. There was a significant difference in age between the groups, as people with in the LBP group were, on average, 7 years older than those in the NoLBP group.

Data collection

Data were collected on age, sex, BMI, and for people with persistent LBP only, pain intensity (numerical rating scale 0-10 using the average of current, usual, and worst pain scores) (Ross, R et al., 1997), activity limitation (Roland Morris Disability Questionnaire) (Roland, M et al., 2000) and a study-specific, non-validated 'does flexion aggravate and extension ease' (FLAG) pain questionnaire. The FLAG is scored from 0-48 where higher scores indicate a greater pattern of flexion-aggravating and extension-easing pain behaviour (see Appendix N). The FLAG has four questions, two that ask about flexion-

aggravating activities and two that ask about extension-easing activities. Each question has two parts: the first part asks about frequency and is scored (a) never =0, rarely =1 sometimes =2, often =3, always =4; and the second part asks about intensity and is scored none =0, low =1, medium =2, and high =3. For each of the four questions, a score is calculated by multiplying frequency (0-4) by intensity responses (0-3) with possible scores of 0-12. Scores for the four questions were then summed to give an indication of the extent to which flexion aggravated and extension eased pain (maximum score = 48).

Movement data were collected using wireless inertial motion and electromyographic (EMG) sensors (ViMove hardware and software, DorsaVi, Melbourne, Australia). Participants were partially undressed, without shoes and stood in a relaxed upright position. Motion sensors were placed over T12 and S2, and EMG sensors applied 1.5 cm either side of L3, using a standardized procedure. Motion sensors were calibrated to zero in the relaxed standing position.

Movements analysed

Movement and positional data were recorded for standing, flexion and sitting. People were asked to stand in their normal standing pose. They were then asked to bend (flex) towards the ground as far they could. A single practice repetition was performed. Three repetitions of flexion with a time count of 3 seconds in the fully flexed position were then performed, using standardized instructions from trained testers and were automatically captured by a computerized process. Patients were then instructed to sit in their usual, full slumped and full upright sitting positions with angular inclination data averaged over 5 seconds for each position once the position was stable. Figure 6.1 demonstrates the sensor placement.

Figure 6.1 Sensor placement

Lumbo-pelvic kinematic parameter definitions

Eight flexion lumbo-pelvic kinematic parameters were assessed during a standing flexion movement including (i) trunk ROM (angular inclination of the trunk at T12), (ii) pelvic ROM (angular inclination of the pelvis at S2), each measured as maximum angular displacement, (iii) lumbar ROM measured as the difference between trunk angular displacement at T12 and pelvic angular displacement at S2, (iv) lumbo-pelvic coordination (also known as lumbo-pelvic rhythm) measured as the percentage of lumbar contribution to trunk movement, using two methods; area under the curve and peak angular displacement, (v) the flexion relaxation response (a response where lumbar extensors muscles show full relaxation in the fully flexed position in healthy individuals (McGorry, RW et al., 2012)) measured as summed EMG activity of extensor muscle activity during the fully flexed position divided by the sum of EMG activity during eccentric (standing to full flexion) and concentric (return from full flexion) phases (vi) the duration/time of eccentric flexion from the start of movement to full flexion where the beginning and end of the movement was determined by a velocity of >7°/sec then <7°/sec respectively, (vii and viii) relative timing of lumbar versus pelvic movement at the beginning of the movement and at 20° (i.e. did both lumbar and pelvic regions move synchronously or was there a time-related delay in the movement of lumbar or pelvic regions at the onset of movement, or in the time it took for each region to achieve 20° of flexion).

The three sitting kinematic parameters included (i) pelvic tilt range, the difference between full posterior and full anterior pelvic tilt as measured by angular inclination at S2, (ii) a 'pelvic tilt ratio' which compared the amount of angular pelvic tilt movement to angular tilting at T12, where numbers >1 indicate more pelvic than trunk movement and numbers <1 indicate more trunk than pelvic movement and (iii) the 'usual' sitting position, a relative sitting position, calculated as a percentage where the slumped sitting angle (full posterior pelvic tilt) was 100% and the angle of upright sitting (full anterior tilt) was 0%. These parameters are described in detail in Appendix P.

A summary of results for flexion and sitting can be seen in Table 6.1 at a group level. Due to a software version evolution between 2011 and 2014, the time related and sitting variables were only available for people measured after 2014 (LBP group = 105 and NoLBP = 100), whereas the range of movement and EMG-related data, were available for all participants.

Table 6.1 Between-group comparisons for demographic and kinematic data

Demographics	Details	*NoLBP* (n=124)	*LBP* (n=140)	p-value
Age (years)		34.4 ± 13.5*	41.4 ± 12.6	**p=.0001**
BMI		23.6 ± 3.5	25.6 ± 4.9	p=.0001
Sex - % female		59%	57%	p=.8250
Pain intensity (0-10)			5.3 ± 1.5	not applicable
Activity limitation (0-100)			39 ± 21	not applicable
Kinematic parameters		No LBP (n=124)	LBP (n=140)	p-value
Flexion: Peak trunk flexion	Trunk flexion angular inclination (T12)	111° ± 16°	93° ± 16°	**p<.0000**
Flexion: Peak lumbar flexion	Lumbar ROM	52° ± 11°	46° ± 12°	**p<.0000**
Flexion: Peak pelvic flexion	Pelvic flexion angular inclination (S2)	59° ± 15°	48° ± 15°	**p<.0000**
Flexion: Lumbo-pelvic co-ordination	Mean Lumbar % contribution	48 ± 11%	49 ± 11%	p=.217
Flexion: Flexion Relaxation Response	A ratio formed by units of surface EMG activity	0.012 ± 0.32	0.25 ± 0.32	**p<.0000**
Sitting: Mean pelvic tilt range	Range from full anterior tilt to full posterior tilt	29° ± 13°	29° ± 13°	p=.883
Sitting: Mean pelvic tilt ratio	A ratio of pelvic tilt range/range of trunk ROM change	2.1 ± 1.3	2.4 ± 1.4	p=.064
Sitting: Mean relative sitting position	Max slump sit = 100%, maximum upright sit = 0%	48 ± 35%	50 ± 35%	p=.619
		No LBP (n=100)	LBP (n=105)	
Flexion: Delay at 0°	Mean delay (negative numbers indicate pelvic delay)	-0.21 ± 0.46sec	-0.36 ± 0.46sec	**p=.023**
Flexion: Delay at 20°	Mean delay (negative numbers indicate pelvic delay)	-0.30 ± 0.88sec	-0.51 ± 0.90sec	p=.105
Flexion: Mean movement duration	Time from start of flexion to full flexion	2.28 ± 0.94sec	3.18 ± 0.94sec	**p<.0000**

* All data represented as mean and standard deviation

Statistical analyses

Latent Class Analysis, a probabilistic form of unsupervised (data-driven) analysis, was used to identify potential subgroup models. Latent Class models were estimated for up to 10 subgroups, using 500 random seed points to reduce the possibility of local solutions. A co-variate consisting of the LBP/NoLBP status of each participant was included in each model to assist in post-hoc analysis but did not contribute to the subgroup modelling. The resultant models were examined for the degree of contributions of each kinematic variable and residual correlations within classes. Model fit was assessed using the Bayesian Information Criterion and informed by posterior probability diagnostics (average posterior probability for each subgroup, classification error and odds of correct classification). We planned to choose the model with the lowest Bayesian Information Criterion score, provided it reduced the criterion score by 1% or more when adding a subgroup (Kongsted, A et al., 2015). Indicator variables that were not contributing to the discrimination of subgroups ($r^2<10\%$) were removed to create more parsimonious models that estimated fewer parameters and had more power. After the final model was chosen, participants were assigned to subgroups based on their individual posterior probability.

A post-hoc analysis of between-subgroup differences was performed, to assist in profiling and subgroup description. For variables that were normally distributed, a one-way analysis of variance was used with post-hoc (unadjusted alpha level = p.05, Bonferroni adjusted alpha level p=.0083) t-test pairwise comparisons. For variables that were not normally distributed, a Kruskal–Wallis Test was used followed by Dunn's test for pair-wise (Bonferroni adjusted) comparisons. Latent Class Analysis was undertaken using Latent GOLD 4.5 (Statistical Innovations Inc, Belmont, CA, USA) and all other statistical procedures used Stata/IC version 15 (StataCorp, College Station, TX, USA).

Ethics

Ethics approval was obtained from the Monash University Human Research Ethics Committee (approval number 2016-1100) and from the Regional Committees on Health Research Ethics for Southern Denmark (approval number S-20110071). All participants were given information about the study and they provided written informed consent.

6.2.4.   Results

Selection of subgroups

Initially, latent class models included all 11 kinematic variables but, as the sitting-related variables all contributed little to the subgroup models (all with an $r^2<4\%$ for each variable), we subsequently removed mean pelvic tilt range, pelvic tilt ratio and usual sitting position from further model building. The model with the lowest eligible Bayesian Information Criterion score, was the four-subgroup model. The mean (SD) probability of membership for subgroups 1 to 4 was 95.1% (10.0%), 91.2% (13.4%), 96.7% (7.7%) and 96.6% (11.1%) respectively, which were considerably above the recommended minimum for model adequacy of 70% (Nagin, D, 2005). Collectively, 92.6% of participants had a posterior probability of >80.0% of belonging to the subgroup into which they were classified and 84.0% of participants had a greater than 90.0% probability. The overall classification error of the four-subgroup model was acceptable at 5.6%.

The odds of correct classification for subgroups 1 to 4 were 19.2, 10.4, 29.4 and 28.2 respectively, well above the minimum value of 5 that is suggested to represent high assignment accuracy (Nagin, D, 2005). Figure 6.2 uses lumbo-pelvic kinematic parameters, normalised to a 0 to 1 scale, to illustrate differences between subgroups. Figure 6.3 provides a clinical interpretation of the four subgroups. Figure 6.4 compares the distribution of people with and without persistent LBP between each of the subgroups.

Movement characteristics of the subgroups

Subgroup 1 was the largest group with 50% of the total cohort (133/266 people) and represented 78% (98/126) of the NoLBP and 25% (35/140) of the LBP groups. This cluster was characterized by the largest trunk ROM with lumbar and pelvic ROM contributing in almost equal parts to trunk flexion, complete relaxation of extensor muscles in full flexion, quicker movement speed and with relatively synchronous movement of pelvic and lumbar spine at the start and also at 20° of movement.

Subgroup 2 represented 17% and 37% of the NoLBP and LBP groups respectively. Compared to subgroup 1, subgroup 2 had less trunk ROM, higher lumbar and lower pelvic angular inclination with greater activation of lumbar extensor muscles, slower movement and a greater delay of pelvic motion

at the start and at 20° of movement, i.e angular inclination occurred through the lumbar spine first, followed by pelvic movement.

Subgroup 3 represented 6% and 24% of the NoLBP and LBP groups respectively. Compared to Subgroup 1, Subgroup 3 had markedly less lumbar movement but similar pelvic angular inclination and was different from Subgroup 2 with a reversed pattern of less lumbar and greater pelvic ROM and with greater lumbar extensor activity at the end of flexion than Subgroups 1 or 2. Subgroup 3 was the only group to have delayed lumbar rather than pelvic motion, i.e angular inclination occurred at the pelvis first, followed then by movement of the lumbar spine.

Subgroup 4 contained only people with LBP (14% of the total LBP group) and also displayed the smallest trunk and pelvic angular inclination of all subgroups, but with comparable lumbar flexion ROM. Subgroup 4 had the poorest flexion relaxation response (highest amount of lumbar extensor activity in the fully flexed position), slowest movement speed and greatest pelvic delay at 20° of movement (see Figure 6.3).

Between-subgroup differences

Table 6.2 displays post hoc analysis of between-subgroup differences. Significant differences were seen for age (Subgroup 1 versus Subgroup 3 only, $p=0.0049$), direction-specific (flexion aggravates, extension eases) pain intensity, activity limitation, percentage of people with leg pain, and for all kinematic parameters, with most p values < 0.001.

Table 6.2 Subgroup descriptions and post hoc analysis

	SubGroup 1	SubGroup 2	SubGroup 3	SubGroup 4	Difference between subgroups
Percentage of total cohort (n=266)	**50% (n=133)**	**27.4% (n=73)**	**15.4% (n=41)**	**7.1% (n=19)**	
Percentage (and number) of people with LBP in each sub group cluster	*26.3% (35)*	*71.2% (52)*	*82.9% (34)*	*100.0% (19)*	
Posterior probability of belonging to each cluster	**0.95 ± 0.10**	**0.91 ± 0.13**	**0.97 ± 0.08**	**0.97 ± 0.11**	
Post hoc analysis – demographics (mean ± *SD)*					
Age	36.5 ± 13.6 [3]	37.5 ± 13.7	42.1 ± 14.8	38.1 ± 13.5	Yes
Sex (female)	60.9%	57.5%	56.1%	47.3%	No
Pain behaviour (for LBP people only) (mean ± *SD)*					
Pain intensity using numerical rating scale (0-10 scale)	5.2 ± 1.4	5.1 ± 1.3	5.6 ± 1.8	5.3 ± 1.5	No
'Flexion aggravates, Extension eases' pain score (0-48 scale) [#]	12.8 ± 7.3 [4]	14.5 ± 8.0 [4]	16.4 ± 8.8 [4]	22.7 ± 8.4 [1,2,3]	Yes
Activity limitation (0-100 scale)	31 ± 17 [4]	38 ± 20	42 ± 22	48 ± 26 [1]	Yes
Percentage of LBP people with leg pain [†]	36.3% [2,4]	52.0% [1,4]	21.8% [4]	76.5% [1,2,3]	Yes
Lumbo-pelvic flexion kinematic parameters (mean ± *SD)*					
Trunk Peak ROM (°)	111 ± 12 [2,3,4]	97 ± 17 [1,3,4]	89 ± 16 [1,2,4]	77 ± 20 [1,2,3]	Yes
Lumbar Peak ROM (°)	51 ± 9 [3]	54 ± 10 [3,4]	30 ± 8.5 [1,2,4]	47 ± 14 [2,3]	Yes
Pelvic ROM (°)	60 ± 11 [2,4]	44 ± 5 [1,4]	59 ± 15 [2,4]	31 ± 11 [1,2,3]	Yes
Percentage of lumbar contribution to trunk flexion (%)	47 ± 7 [2,3,4]	57 ± 10 [1,3]	35 ± 9 [1,2,4]	60 ± 9 [1,3]	Yes
Flexion relaxation response	0.00 ± 0.00 [2,3,4]	0.04 ± 0.05 [3,4]	0.48 ± 0.50 [1,2]	0.72 ± 0.55 [1,2]	Yes
Duration of trunk flexion (sec)	2.31 ± 0.63 [,2,3,4]	3.11 ± 1.11 [1]	2.87 ± 0.70 [1]	4.10 ± *1.83* [1]	Yes
Pelvic time-lag at start of movement (sec)*	+0.17 ± 0.14 [2,4]	+0.42 ± 0.31 [1,3]	+0.13 ± 0.24 [2,4]	+1.10 ± 1.34 [1,3]	Yes
Pelvic time-lag at 20° of movement (sec)*	+0.22 ± 0.30 [2,4]	+0.86 ± 0.53 [1,4]	- 0.55 ± 0.8 [4]	+2.04 ± 1.74 [1,2,3]	Yes

Superscript numbers represent subgroups i.e. 3 = Subgroup3 and indicate a significant difference between the column named subgroup and the superscripted subgroup. For p values, see Appendix Q.
 # A study-specific, non-validated questionnaire based on directional pain responses where flexion aggravates and extension eases (see Appendix N).
† Percentage calculated by number of people with leg pain in each subgroup over number of people with LBP in each subgroup.
* positive numbers indicate a time-lag (delay) of pelvic movement, i.e the lumbar spine moves first then the pelvis begins to move, lagging behind lumbar movement (at start and at 20o of lumbar and pelvic flexion). Negative numbers indicate a time-lag for the lumbar spine, i.e. the pelvis moves or achieves 20o of flexion earlier than the lumbar spine achieving 20o.

Figure 6.2 Comparisons of the means for each subgroup on each kinematic parameter

(scale normalised to 0-1)*
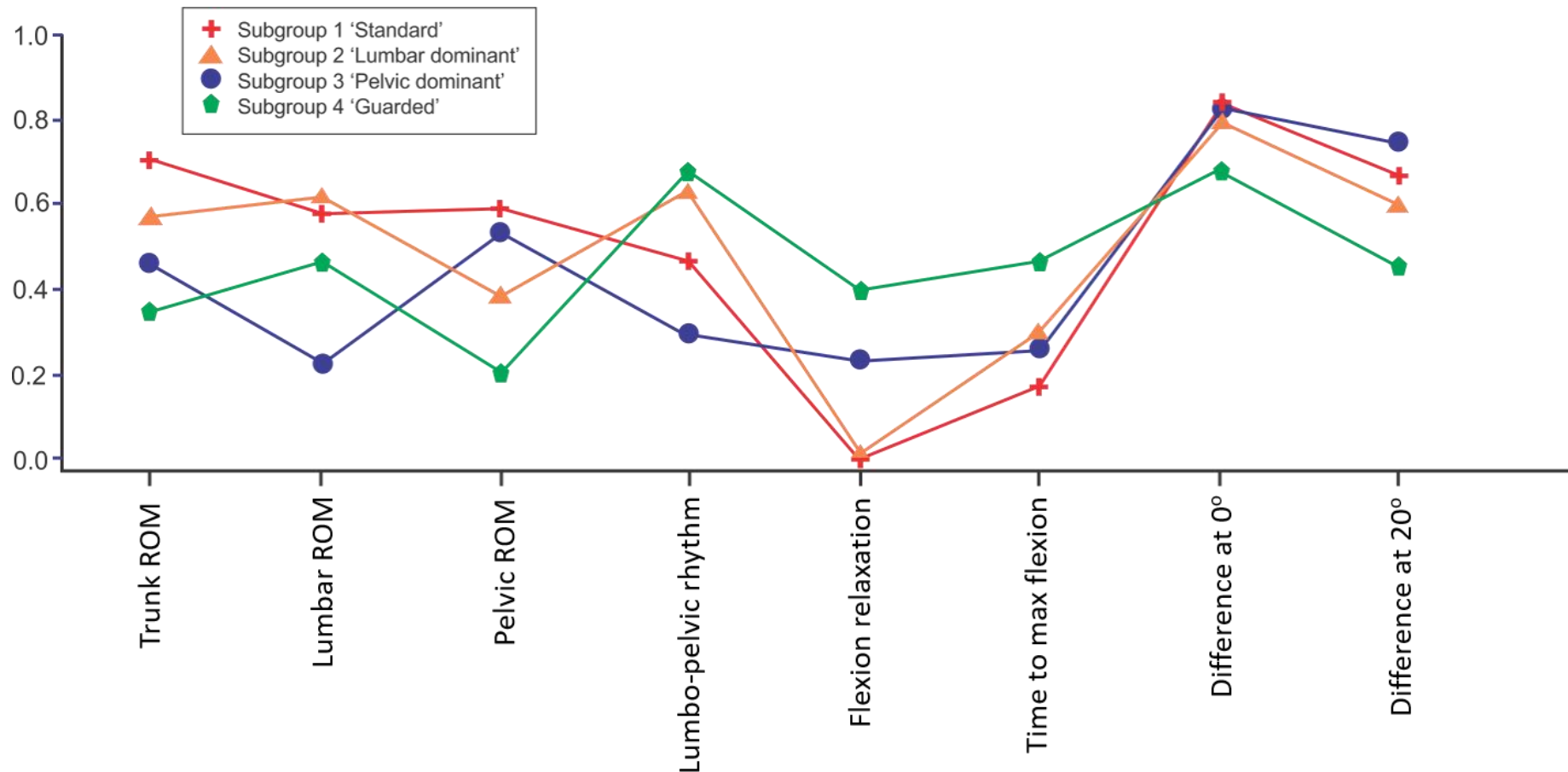
Figure 6.2 illustrates a clinical visualization for each subgroup, with angular inclination for trunk (at T12), pelvis angular inclination (at S2), lumbar movement range and lumbar extension muscle activity (with movement duration and pelvic or lumbar delay at 20° added as text below each subgroup).

* On the normalised scale of 0-1, 0 is the lowest score observed and 1 is the highest score, with the mean value indicated for each subgroup.

Figure 6.3 Clinical visualization of mean peak kinematic parameters, temporal and muscle relaxation parameters for each subgroup

	Subgroup 1 'Standard'	Subgroup 2 'Lumbar dominant'	Subgroup 3 'Pelvic dominant'	Subgroup 4 'Guarded'
Time to maximum flexion:	2.31 sec	3.11 sec	2.87 sec	4.10 sec
Pelvic or Lumbar delay at 20°:	Pelvic 0.2 sec	Pelvic 0.9 sec	Lumbar 0.6 sec	Pelvic 2.0 sec
Flexion relaxation ratio values:	0.00	0.04	0.48	0.72

= increased activation of lumbar extensor muscles in the fully flexed position
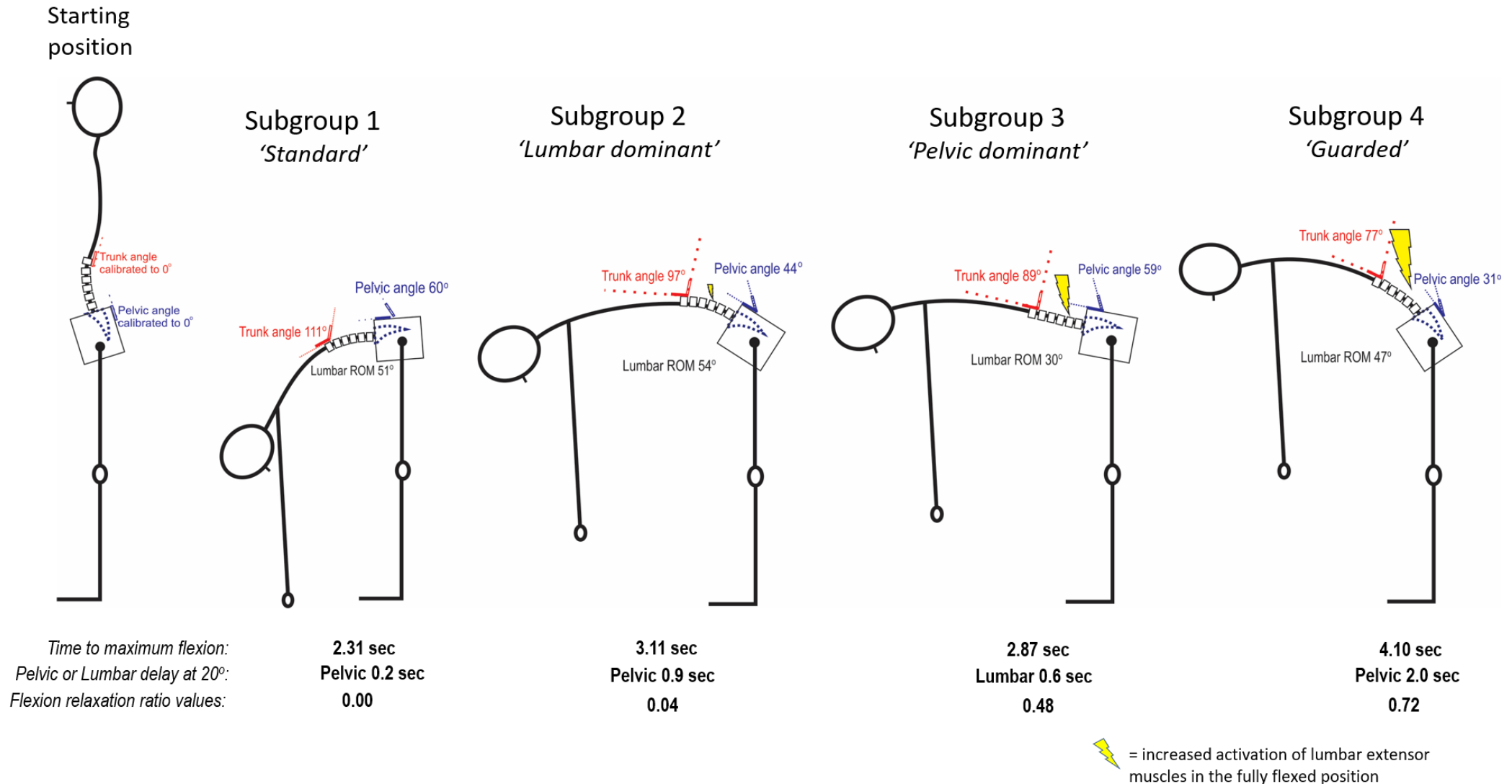
This figure illustrates the four-subgroup solution with the image describing each parameter using normalized means where 1= the maximum value and 0=0. For ROM, higher values indicate larger ROM, for lumbo-pelvic rhythm (lumbo-pelvic coordination) higher scores indicate a larger percentage of lumbar contribution, for 'time to max flexion' larger scores indicate slower movement, for 'difference at 0o and 20o' lesser scores indicate a lag of pelvic (versus lumbar) movement with the greatest score indicating a lag of lumbar movement

Figure 6.4 Comparison of the percentage of NoLBP versus LBP people in each group
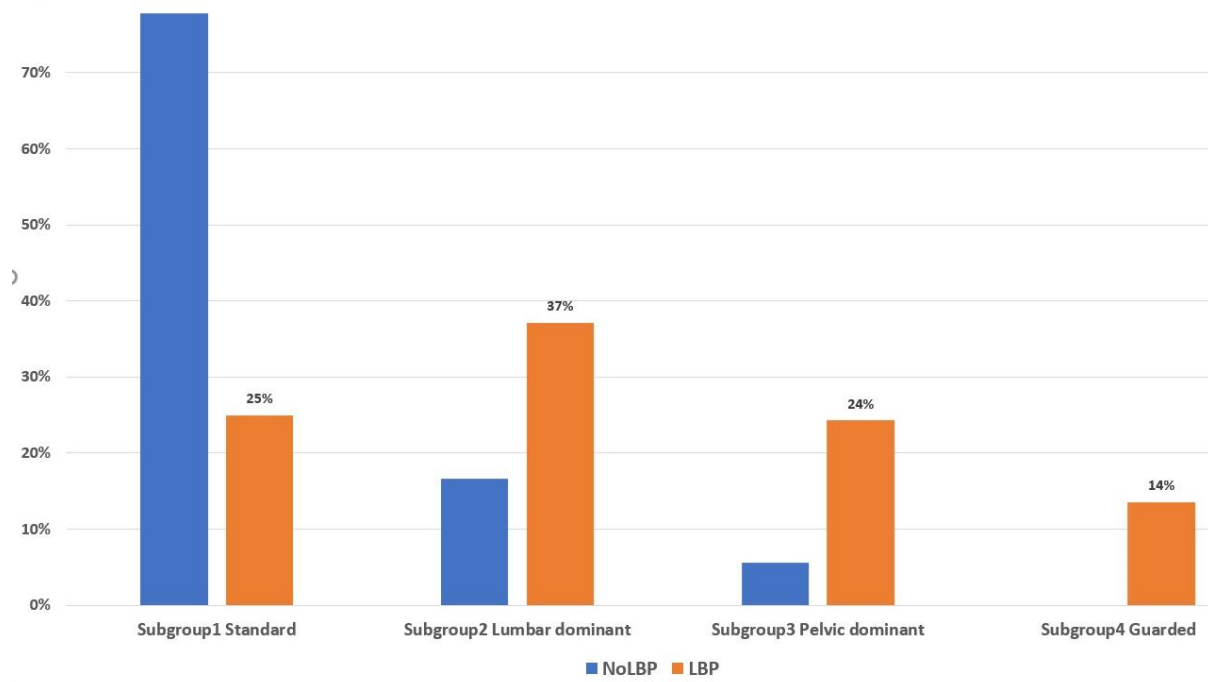
Figure 6.4 displays the percentage distribution of people with and without LBP in each subgroup. No people without LBP were seen in Subgroup 4.

6.2.5.   Discussion

This study used data from a previous observational cohort study to examine whether patterns of movement could be seen in multivariable flexion-related lumbo-pelvic kinematics (eight standing flexion parameters and three sitting parameters) and if these patterns occurred equally in people with and without persistent LBP. Latent Class Analysis identified four relatively well-defined subgroups with three of the subgroups containing both NoLBP and LBP participants, and one subgroup consisting of LBP participants only. These results support the concept that people demonstrate heterogenous movement characteristics, and some of those patterns are associated with persistent LBP. These findings align with the heterogeneity reported in and across other health data such as cognitions, pain behaviour, and improvement trajectories.

The concept of movement-related subgroups is not new. Two of the movement patterns identified in this sample are similar to patterns described in other classification systems such as the flexion and 'active-extension' motor control impairment described by O'Sullivan (Dankaerts, W et al., 2009; O'Sullivan, P., 2005b) with Subgroup 2 and Subgroup 3 respectively matching these descriptive groups.

Several studies using pre-classified groups have identified kinematic differences between flexion and 'active extension' subgroups, and between people with LBP and healthy controls (Dankaerts, W et al., 2009; Dankaerts, W. et al., 2006e; Gombatto, S et al., 2017; Hemming, R et al., 2017). However, in all of these studies, subgroups were pre-defined based on observation and history, without objective measurement of lumbo-pelvic kinematics, and analysed smaller samples. Where studies subsequently contrasted those subgroups using laboratory-based measurement tools, these contrasts were usually only univariate comparisons. This study differs by using multivariable clusters of lumbo-pelvic kinematic parameters to describe patterns that are seen in both NoLBP and LBP populations, in a large sample using wireless motion and surface EMG sensors that are readily available for clinical settings.

The relationship between movement and pain

Subgroups 1, 2, and 3 all included people who reported never having had LBP that warranted seeing a clinician or taking time off work or sport. The presence of people with no history of LBP in these subgroups, particularly Subgroups 2 and 3, suggest that these movement patterns can pre-exist injury or a chronic pain experience. The decreasing percentage of people with no LBP history within Subgroups 2-4 suggests that pain and movement are associated, and that identifying cause and/or consequence relationships between pain and movement is likely to be important. Subgroup 4 included only people from the LBP group. The observed reduced movement range and increased muscle activation may be protective of, or a reactive response to, pain. However, we do not know if pre-existing movement patterns, such as those seen in Subgroups 2 and 3, increase the risk of developing LBP. Further research is required to see if the presence of a particular movement pattern or specific lumbo-pelvic kinematic parameter increases the risk of LBP occurrence, delays recovery or is associated with differing trajectories of recovery.

The mean pain score did not differentiate between subgroups, a finding previously seen in other subgrouping studies (Hemming, R et al., 2017). However, direction-specific pain questions (does flexion aggravate and extension ease pain?) showed increasing pain scores with correspondingly reduced ROM from Subgroups 1 to 4 and increasingly reduced flexion relaxation. Clinicians often observe a pain response matched to directionally specific movement ((Long, A et al., 2004; Maitland, G, 1991; Sahrmann, S, 2002a), so this relationship between flexion aggravation pain scores and flexion kinematics is not surprising. A similar pattern of progressively increased activity limitation from

Subgroups 1 to 4 was seen and is consistent with the direction-specific pain score that quantified flexion-related pain activities. Leg pain and pelvic ROM also showed the interesting and clinical plausibile finding where the two subgroups that had the lowest pelvic ROM also had the largest percentage of people with a leg pain component associated with their LBP (52% and 76% for Subgroups 2 and 4 compared to 36% and 22% for Subgroups 1 and 3).

Implications for research and clinical management

The presence of relatively distinct and different patterns lends support to the concept that treatments are likely to be more effective if the treatment matches the identified deficit. For example, improving the flexion relaxation response is recommended for people with persistent LBP and may be helpful for people in Subgroups 3 and 4 but is unlikely to assist when people with persistent LBP have the flexion movement pattern seen in Subgroups 1 and 2. Similarly, improving lumbar ROM may be helpful for people in Subgroup 3, where lumbar flexion has the greatest reduction, but is less likely to be useful for people in Subgroup 4 where lumbar flexion is only slightly less than almost 80% of the NoLBP group. While there is limited evidence that individualized treatment approaches have favourable outcomes (Fersum, KV et al., 2012; Ford, JJ et al., 2016; Kent, P et al., 2015a; Long, A et al., 2004), it is unknown if treatments aimed at specific kinematic subgroups have better outcomes. If these subgroups continue to be seen in other samples, matching specific treatments to subgroups based on lumbo-pelvic kinematics could be a focus for further research.

While pain and activity limitation are seen to some extent in most LBP patients, this is not necessarily true for the presence of some lumbo-pelvic kinematic features. In this sample, 25% of people with chronic LBP had a 'standard' pattern of movement that was found in almost 80% of the NoLBP group, suggesting that people in this subgroup have flexion kinematics that are not obviously affected by pain and are the same as people without LBP. It is possible that other unmeasured parameters (e.g. ROM in other directions, different muscle activation patterns or strength factors) might have been problematic or it may be that movement factors are not relevant for some people with LBP. This has implications for research and measuring change in movement as an outcome measure. Measuring changes to pain and activity limitation are relevant to most LBP patients but measuring change to movement is less relevant for some people.

Strengths

Classification accuracy was high which provides greater confidence in observing subgroup patterns. The sample size was sufficiently large to observe non-predetermined patterns. An additional benefit was the inclusion of 126 people with no history of significant back pain which allowed insight into whether movement patterns could pre-exist the onset of pain.

There are clinically relevant strengths of this study. The use of single, univariable comparisons has frequently been used to contrast NoLBP and LBP groups, with varying results (Laird, R et al., 2014). A strength of using multivariable lumbo-kinematic parameter analysis that uses clusters of parameters to define patterns (subgroups) of patients is that it reflects real-world clinical practice which incorporates many sources of information in decision-making. For example, including pelvic ROM as one of the flexion-related lumbo-pelvic parameters combined with the flexion relaxation response helped differentiate between Subgroups 2 and 4. Conversely, if lumbar ROM were the main measure of physical assessment without reference to other measures, the distinction between those subgroups would not be possible. Another clinically relevant strength is that the lumbo-pelvic kinematic parameters used in this study can all be measured in a typical clinical setting.

Limitations

Flexion was chosen as the focus of kinematic assessment because flexion-related activities have been previously identified as the most common pain-related activities in people with LBP (Pengel, LH et al., 2004). Additionally, previous work has shown that flexion has greater measurement reliability and consistency compared to other directions, most likely due to the larger relative ROM, limited effect of attenuation of range on correlational indices, and lower susceptibility to skin movement artefacts (Laird, R et al., 2016). However, other movement directions and parameters (i.e strength, proprioception) may also inform clinical decision-making. The inclusion of other movement-related parameters are likely to add to, and change, overall subgroup profiles. It is also possible that while flexion was not problematic for some of the people with persistent LBP in this sample, other movement directions, e.g. extension, could have been painful for them. Also, functional tasks are often three dimensional, whereas this sample of people were tested using sagittal plane motion only. However, Marras et al (1999a) and Gombatto et al (2017) both assessed para-sagittal and three-dimensional movement, with both studies demonstrating that the sagittal plane was the movement plane where movement effects were most visible. It would both be very difficult to assemble a sample of people who had never experienced any

LBP at any time point, and the results from such a group would not be broadly applicable to the general population. In addition, age can affect ROM and there was a significant difference in age only between Subgroups 1 and 3 of approximately 6 years. In our view, that difference is unlikely to account for the 21° difference of lumbar ROM seen between those subgroups. Another limitation of the study was that other pain-related parameters such as duration of pain and frequency of recurrence may have provided additional information about subgroup characteristics. Lastly, these results have not been verified in an independent sample and, until such time, the possibility that observed clusters are sample specific, must be considered.

6.2.6.   Conclusion

Movement was studied in 140 people with and 126 people without persistent LBP, with four movement-pattern subgroups seen in flexion related lumbo-pelvic kinematics. Subgroup 1, the 'standard' group was the largest, accounting for almost 80% of NoLBP and 25% of people with LBP and 50% of the total group. Subgroup 1 ('standard' subgroup) had the greatest trunk ROM, full flexion relaxation at end range flexion, and relatively synchronous pelvic and lumbar movement. Subgroups 2 ('lumbar-dominant') and 3 ('pelvic-dominant') showed progressive loss of flexion relaxation and opposite lumbo-pelvic rhythm patterns. Subgroup 4 ('guarded' movement) had the lowest trunk and pelvic ROM, but similar lumbar ROM to the standard subgroup, had the highest extensor muscle activation in full flexion, the slowest movement, and the greatest pelvic delay. In addition, leg pain occurred more frequently in the two subgroups that had the lowest range of pelvic movement. Although mean pain intensity scores were similar across subgroups, activity limitation and the 'flexion aggravates/extension eases' pain scores progressively increased, reaching significance for the comparison between Subgroup 1 (standard) and Subgroup 4 (guarded). These results indicate that different patterns of flexion are present in people with and without persistent LBP and this has implications for both further research and treatment.

Abbreviations

LBP = Low Back Pain
NoLBP = participants without low back pain

RMDQ = Roland Morris Disability Questionnaire

ROM = Range of motion

FRR = Flexion relaxation response

Declarations

Ethics approval and consent to participate

This research project was performed in accordance with the Declaration of Helsinki with approval obtained from the Monash University Human Research Ethics Committee (approval number CF12/1995-20 12001090, 2016-1100) and the Regional Committees on Health Research Ethics for Southern Denmark (approval number S-20110071). All participants gave written informed consent for testing and use of de-identified data, through the use of an ethics committee-approved patient information and consent form.

Consent for publication

All participants were provided with a Monash University Human Research Ethics Committee-approved patient information and consent form, which included consent for publication. All participants provided signed consent forms before being admitted into the study.

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to the data being used for further research in a current PhD project, but are available from the corresponding author on reasonable request. All raw data and information related to additional files can be obtained from the first author at robert.laird@monash.edu.

Competing interests

No benefits in any form have been, or will be, received for this study from a commercial party related directly or indirectly to the subject of this paper. This paper does not contain information about drugs. The authors do not hold stocks or shares in any company that might be directly or indirectly affected by this study. No patents have been applied for or received due to the content of this paper and there are no non-financial competing interests associated with this paper.

Funding

No funding was received for this study.

Authors' contributions

RL contributed to data collection. RL was the main author of this paper, leading the concept, writing, data analysis, interpretation, draft revision and gave approval of the final manuscript. JK and PK both provided concept guidance, statistical direction, analysis, draft revision and gave approval of the final manuscript. RL, JK and PK agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

6.2.7. Bibliography for Laird et al (2018B)

Abboud, J., Nougarou, F., Page, I., Cantin, V., Massicote, D., & Descarreaux, M. (2014). Trunk motor variability in patients with non-specific chronic low back pain. *European Journal of Applied Physiology*.

Borkan, J. M. M. D. P., Koes, B. P., Reis, S. M. D., & Cherkin, D. C. P. (1998). A Report From the Second International Forum for Primary Care Research on Low Back Pain: Reexamining Priorities. *Spine, 23*(18), 1992-1996.

Costa, L. d. C. M. P., Koes, B. W. M. D. P., Pransky, G. M. D. M. O. H., Borkan, J. M. D. P., Maher, C. G. M. D. P., & Smeets, R. J. E. M. M. D. P. (2013). Primary Care Research Priorities in Low Back Pain: An Update. *Spine, 38*(2), 148-156.

Dankaerts, W., O'Sullivan, P., Burnett, A., Straker, L., Davey, P., & Gupta, R. (2009). Discriminating healthy controls and two clinical subgroups of nonspecific chronic low back pain patients using trunk muscle activation and lumbosacral kinematics of postures and movements: A statistical classification model. *Spine, 34*(15), 1610-1618.

Dankaerts, W., O'Sullivan, P., Burnett, A., & Straker, L. (2006). Altered patterns of superficial trunk muscle activation during sitting in nonspecific chronic low back pain patients: Importance of subclassification. *Spine, 31*(17), 2017-2023.

Delitto, A., Erhard, R. E., & Bowling, R. W. (1995). A treatment-based classification approach to low back syndrome: identifying and staging patients for conservative treatment... including commentary by DeRosa CP and Greathouse DG with author response. *Physical Therapy, 75*(6), 470-489.

Deyo, R., Bryan, M., Comstock, B., Turner, J., Heagerty, P., Friedly, J., et al. (2015). Trajectories of Symptoms and Function in Older Adults With Low Back Disorders. *Spine, 40*(17), 1352-1362.

Fersum, K. V., O'Sullivan, P., Skouen, J. S., Smith, A., & Kvale, A. (2012). Efficacy of classification-based cognitive functional therapy in patients with non-specific chronic low back pain: A randomized controlled trial. *European Journal of Pain, 17*(6), 916-928.

Floyd, W., & Silver, P. (1951). The function of the erectores spinae muscles in flexion of the trunk. *Lancet, 6647*, 123-133.

Ford, J. J., Hahne, A. J., Surkitt, L. D., Chan, A. Y., Richards, M. C., Slater, S. L., et al. (2016). Individualised physiotherapy as an adjunct to guideline-based advice for low back disorders in primary care: a randomised controlled trial. *British Journal of Sports Medicine, 50*(4), 237-245.

Geisser, M. E., Ranavaya, M., Haig, A. J., Roth, R. S., Zucker, R., Ambroz, C., et al. (2005). A meta-analytic review of surface electromyography among persons with low back pain and normal, healthy controls. *Journal of Pain, 6*(11), 711-726.

Gombatto, S., D'Arpa, N., Landerholm, S., Mateo, C., O'Connor, R., Tokunaga, J., et al. (2017). Differnece in kinematics of the lumbar spine and lower extremities between poeple with and wihtout low back pain during the down phase of a pick up task, an observational study. *Musculoskeletal Science and Practice, 28*, 25-31.

Hemming, R., Sheeran, L., van Deursen, R., & Sparkes, V. (2017). Non-specific chronic low back pain: differences in spinal kinematics in subgroups during functional tasks. *European Spine Journal, 27*(1), 163-170.

Hodges, P., Cholewicki, J., & Van Dieen, J. (2013). *Spinal Control: the rehabilitation of back pain* (P. Hodges, J. Cholewicki, & J. Van Dieen Eds.). Edinburgh: Elsevier.

Hodges, P. W., Coppieters, M. W., MacDonald, D., & Cholewicki, J. (2013). New insight into motor adaptation to pain revealed by a combination of modelling and empirical approaches. *European Journal of Pain, 17*(8), 1138-1146.

Karayannis, N., Jull, G., & Hodges, P. (2012). Physiotherapy movement based classification approaches to low back pain: comparison of subgroups through review and developer/expert survey. *BMC Musculoskeletal Disorders, 13*(24).

Kent, P., Laird, R., & Haines, T. (2015). The effect of changing movement and posture using motion-sensor biofeedback, versus guidelines-based care, on the clinical outcomes of people with sub-acute or chronic

low back pain-a multicentre, cluster-randomised, placebo-controlled, pilot trial. *BMC Musculoskeletal Disorders*(16), 131-150.

Kongsted, A., Kent, P., Albert, h., Jensen, T., & Manniche, C. (2012). Patients with low back pain differ from those who also have leg pain or signs of nerve root involvement – a cross-sectional study. *BMC Musculoskeletal Disorders, 12*, 236-245.

Kongsted, A., Kent, P., Hestbaek, L., & Vach, W. (2015). Patients with low back pain had distinct clinical course patterns that were typically neither complete recovery nor constant pain. A latent class analysis of longitudinal data. *The Spine Journal, 15*, 885-894.

Laird, R., Gilbert, J., Kent, P., & Keating, J. (2014). Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis. *BMC Musculoskeletal Disorders, 15*(1), 229.

Laird, R., Kent, P., & Keating, J. (2016). How consistent are lordosis, range of movement and lumbo-pelvic rhythm in people with and without back pain? *BMC Musculoskeletal Disorders*(17), 403-417.

Long, A., Donelson, R., & Fung, T. (2004). Does it matter which exercise? A randomized control trial of exercise for low back pain. *Spine, 29*(23), 2593-2602.

Maitland, G. (1991). *Peripheral manipulation* (3rd ed.). London: Butterworth-Heinemann.

Marin, T. J., Van Eerd, D., Irvin, E., Couban, R., Koes, B. W., Malmivaara, A., et al. (2017). Multidisciplinary biopsychosocial rehabilitation for subacute low back pain. *Cochrane Database of Systematic Reviews*(6).

Marras, W. S., Ferguson, S. A., Gupta, P., Bose, S., Parnianpour, M., Kim, J. Y., et al. (1999a). The quantification of low back disorder using motion measures: Methodology and validation. *Spine, 24*(20), 2091-2100.

Marras, W. S., Ferguson, S. A., Gupta, P., Bose, S., Parnianpour, M., Kim, J. Y., et al. (1999b). The quantifications of low back disorder using motion measures: methodology and validation. *Spine, 24*(20), 2091-2100.

Marras, W. S., Parnianpour, M., Ferguson, S. A., Kim, J. Y., Crowell, R. R., Bose, S., et al. (1995). The classification of anatomic- and symptom-based low back disorders using motion measure models. *Spine, 20*(23), 2531-2546.

Mayer, T. G., Neblett, R., Brede, E., & Gatchel, R. J. (2009). The quantified lumbar flexion-relaxation phenomenon is a useful measurement of improvement in a functional restoration program. *Spine, 34*(22), 2458-2465.

McGorry, R. W., & Lin, J.-H. (2012). Flexion relaxation and its relation to pain and function over the duration of a back pain episode. *PLoS ONE [Electronic Resource], 7*(6), e39207.

McKenzie, R., & May, S. (2003). *Lumbar Spine, Mechanical Diagnosis and Therapy* (2nd ed.). Waikanae, New Zealand: Spinal Publications Ltd.

Nagin, D. (2005). *Group-based modeling development*. Cambridge: Harvard University Press.

Neblett, R., Mayer, T. G., Brede, E., & Gatchel, R. J. (2014). The effect of prior lumbar surgeries on the flexion relaxation phenomenon and its responsiveness to rehabilitative treatment. *The Spine Journal, 14*, 892-902.

O'Connell, G. D., Vresilovic, E. J., & Elliott, D. M. (2011). Human intervertebral disc internal strain in compression: The effect of disc region, loading position, and degeneration. *Journal of Orthopaedic Research, 29*(4), 547-555.

O'Sullivan, P. (2005). Diagnosis and classification of chronic low back pain disorders: maladaptive movement and motor control impairments as underlying mechanism. *Manual Therapy, 10*(4), 242-255.

O'Sullivan, P., Smith, A., Beales, D., & Straker, L. (2017). Understanding Adolescent Low Back Pain From a Multidimensional Perspective: Implications for Management. *Journal of Orthopaedic & Sports Physical Therapy, 47*(10), 741-751.

O'Sullivan, P. B. (2005). Diagnosis and classification of chronic low backpain disorders: Maladaptive movement and motor control impairments as underlying mechanism. *Manual Therapy, 10*, 242-255.

Pengel, L. H., Refshauge, K. M., & Maher, C. G. (2004). Responsiveness of pain, disability, and physical impairment outcomes in patients with low back pain. *Spine, 29*(8), 879-883.

Roland, M., & Fairbank, J. (2000). The Roland-Morris Disability Questionnaire and the Oswestry Disability Questionnaire. *Spine, 25*(24), 3115-3124.

Ross, R., & LaStayo, P. (1997). Clinical assessment of pain. In J. van Deusen & D. Brunt (Eds.), *Assessment in Occupational Therapy and Physical Therapy*. Philadelphia: WB Saunders Co.

Sahrmann, S. (2002). *Diagnosis and treatment of movement impairment syndromes*. St. Louis: Mosby.

Sahrmann S. (2002). Movement impairment syndromes of the lumbar spine.In: Diagnosis and treatment of movement impairment syndromes. *Diagnosis and treatment of movement impairment syndromes.*

 (1st ed., pp. 5-118). St. Loius: Mosby Inc.

Seay, J. F., E.A, & Hamill, J. (2011). Low back pain status affects pelvis-trunk coordination and variability during walking and running. *Clinical Biomechanics, 26*(6), 572-578.

Villumsen, M., Madeleine, P., Jorgensen, M., Holtermann, A., & Samani, A. (2016). The variability of the trunk forward bending in standing activities during work vs. leisure time. *Applied Ergonomics, 58*, 273-280.

Waddell, G. (1987). A new clinical model for the treatment of low-back pain. *Spine, 12*(7), 632-644.

Wong, T. K., Lee, R. Y., Wong, T. K. T., & Lee, R. Y. W. (2004). Effects of low back pain on the relationship between the movements of the lumbar spine and hip. *Human Movement Science, 23*(1), 21-34.

6.3.   Summary and application of results

The results of this paper indicated four distinct patterns of standing flexion movement in this cohort of people with and without persistent LBP, providing empirical support for the clinically inspired notion that different patterns of movement are present in people with and without LBP.

6.3.1.   Additional information on the use of latent class analysis

Latent Class models were estimated for up to 10 subgroups, using 500 random seed points to reduce the possibility of local solutions. A co-variate consisting of the LBP/NoLBP status of each participant was included in each model to assist in post-hoc analysis but did not contribute to the subgroup modelling. The resultant models were examined for the degree of contributions of each kinematic variable and residual correlations within classes. Model fit was assessed using the Bayesian Information Criterion and informed by posterior probability diagnostics (average posterior probability for each subgroup, classification error and odds of correct classification). We chose the model with the lowest Bayesian Information Criterion score, provided it reduced the criterion score by 1% or more when adding a subgroup (Kongsted, A et al., 2015). Indicator variables that were not contributing to the discrimination of subgroups ($r^2 < 10\%$) were removed to create more parsimonious models that estimated fewer parameters and had more power. After the final model was chosen, participants were assigned to subgroups based on their individual posterior probability.

6.3.2.   Movement patterns in people without a history of LBP

In our analysis we were particularly interested in whether observed patterns were typical of movement patterns of all people (with or without back pain) or were specific to those with LBP. The inclusion of people without pain into this cohort was revealing, with 78% of the NoLBP group belonging to the 'standard' movement subgroup. The 'standard' subgroup had the largest ROM, the greatest degree of synchronous lumbar and pelvic motion, the fastest movement speed and full FRR (minimal or no lumbar extensor muscle activation in the fully flexed position). The implication from this is that there may be a typical flexion movement patterns common to the majority of people without a history of LBP, assuming that this cohort is typical of the general community. There is variation expected, and seen, in the NoLBP group but the distribution of the NoLBP group was not uniform across the movement subgroups. Sixteen percent of people without pain were seen in the 'lumbar dominant'

subgroup, only six percent in the 'pelvic dominant' subgroup, and none in the 'guarded' subgroup. The uneven distribution of people without LBP across movement subgroups increases curiosity about whether patterns of movement, rather than single lumbo-pelvic kinematic parameters, could be used as prognostic variables to predict the risk of developing LBP or having relapses. Alternatively, it may also be that these patterns have no relationship to LBP development or recurrence. Another explanation might be that although the NoLBP group stated they had never had an episode of LBP that required seeing a health professional, or taking time off work or sport, they may have experienced mild pain which has influenced their subsequent movement patterns.

6.3.3.   Movement patterns in people with persistent LBP

Standard movement pattern

In contrast to the NoLBP group, people in the LBP group were found in all four subgroups. One in four people (25%) of the LBP group belonged to the 'standard' or typical movement pattern, suggesting that for these people, *flexion-related* movement had not been affected by the presence of pain. These people may have had atypical movement in other directions (extension, lateral flexion, rotation) or in other movement-related parameters such as strength, functional activity, and/or posture, or they may not have any atypical movements at all.

Lumbar and pelvic dominant movement patterns

When comparing **between groups**, there was no difference in flexion lumbo-pelvic rhythm (as measured by the peak angle percentage of lumbar ROM contribution for trunk flexion) using univariate comparisons i.e. NoLBP (48% SD*± 11%)* compared with the LBP group (49% *± 11%)* (Laird, R et al., 2018A). However, this multivariable analysis provided new insights into this lumbo-pelvic kinematic parameter with significant differences seen when comparing **between subgroups**. The lumbar dominant subgroup had a significantly greater percentage of lumbar contribution to flexion (57%*±10%, p<.0000)* compared with the standard subgroup (47%*±7%)*. This also contrasts with the pelvic dominant subgroup that had a significantly smaller percentage of lumbar movement contributing to flexion (35%*±9%, p<.0000)*. The timing of movement also varied across subgroups. Both lumbar and pelvic dominant subgroups have a slight delay (lag) of pelvic movement at the onset of flexion (i.e the lumbar spine moves first, then the pelvis follows). However, at 20° of movement, the lumbar-dominant subgroup

had a ***pelvic delay*** (i.e the lumbar spine achieved 20° of flexion earlier than the pelvis) which contrasts with the pelvic dominant subgroup that had an opposite pattern of ***lumbar delay*** (i.e. the pelvis achieved 20° of flexion earlier than the lumbar spine). The implications are discussed within Laird et al. (2018B) but in summary, these differing patterns may call for differing movement-based interventions (discussed in Chapter 7 under sections 7.2 and 7.3) and warrants future investigation. Figure 6.5 illustrates the different flexion movements in two people, one with a lumbar dominant pattern and one with a pelvic dominant pattern.

Figure 6.5 Clinical images of lumbar and pelvic dominant patterns of movement
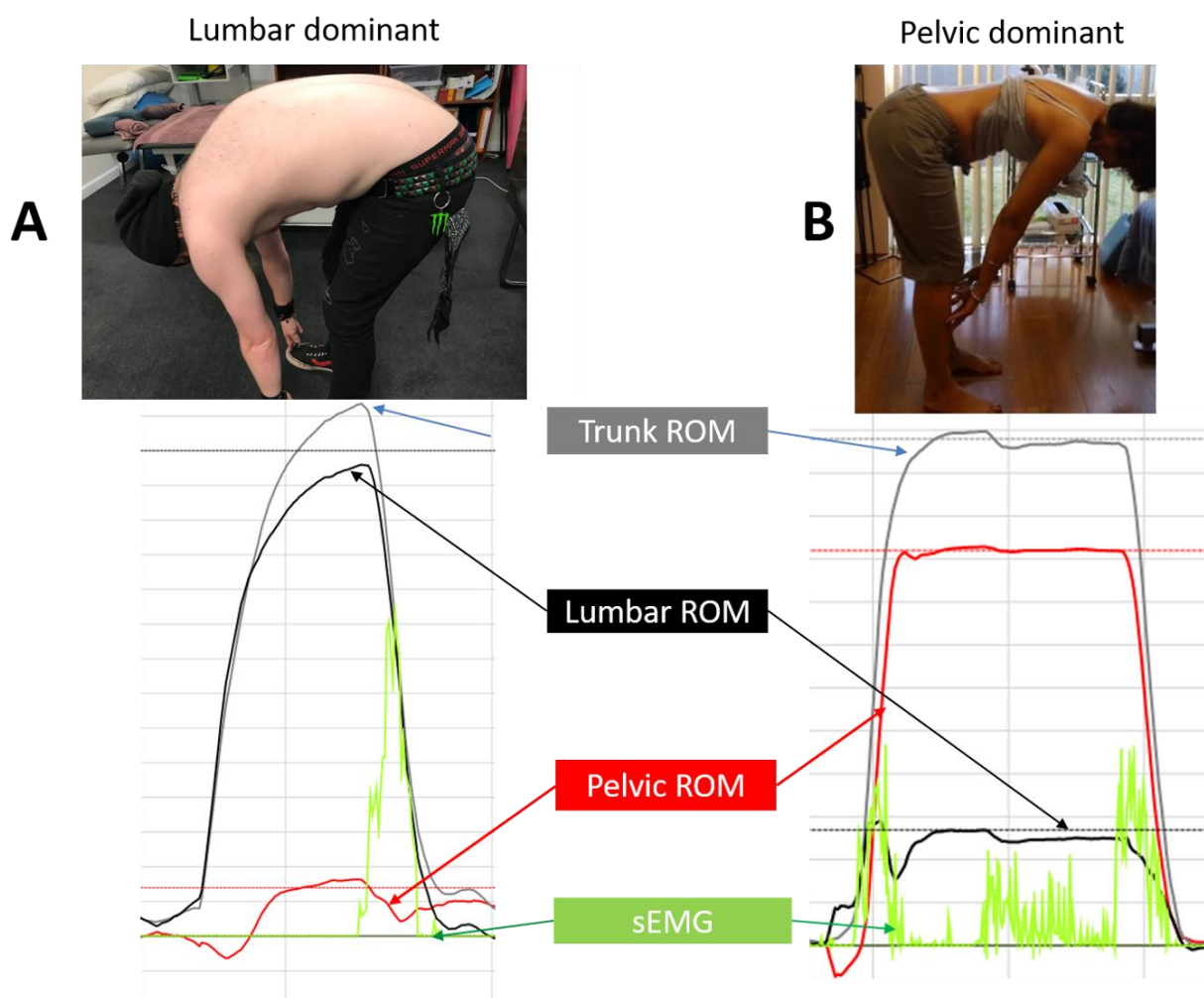
Figure 6.5: Image A illustrates a 'lumbar dominant' pattern and image B depicts a 'pelvic dominant' pattern. The graphs below each image describe the ROM with angular inclination at T12/trunk (grey line), at S2/pelvis (red line) and for lumbar ROM (black line). The green line indicates lumbar extensor muscle activity. Images copyrighted to R. Laird.

Subgroup four (guarded pattern**)**

Only 19 of 140 people with persistent LBP were seen in the guarded subgroup (14% of the LBP group) with most lumbo-pelvic kinematic parameters significantly different from all other subgroups *except* for lumbar ROM. People in the guarded subgroup had the lowest FRR (highest amount of electrical activity of lumbar extensors in the fully flexed position), the smallest trunk and pelvic ROM, and the slowest movement. They also had the

highest activity limitation and 'flexion aggravates/extension eases' pain scores. Because only people with LBP demonstrated a guarding pattern of movement, it is reasonable to consider that a guarding pattern is related to a cause of, or response to, pain.

6.4. Parallels with other biomechanical data and with clinical classification systems

The results from Laird et al. (2018B) appear to be the first empirical approach to describe subgroups/patterns based solely on flexion-related kinematics (a data-driven approach) without any pre-hoc classification of subgroup definitions. Other studies have used kinematic data to validate pre-defined subgroups (Dankaerts, W et al., 2009; Gombatto, SP et al., 2007; Marras, WS et al., 1995b; Mayer, T et al., 2009) but have not used lumbo-pelvic kinematic parameter data models to define data-driven classification.

The patterns/subgroups described in Laird et al. 2018B align to some extent with the work of others. Mayer et al. (2009) analysed a prospective cohort of people with persistent LBP (n=135), measuring trunk, lumbar, pelvic ROM and FRR. They classified their cohort, a priori, using previously developed cut-points, into belonging to one of four groups; (1) normal ROM and EMG, (2) abnormal ROM and normal EMG, (3) normal ROM and abnormal EMG and (4) abnormal ROM and EMG. The main aim of that study was to assess the responsiveness of aberrant FRR to change following a functional restoration program. Their description of four groups is similar to the patterns/subgroups reported in Laird et al. (2018B). Table 6.1 compares the ROM and EMG measurements from Mayer et al. (2009) and Laird et al. (2018B). The standard subgroup reported by Laird et al. corresponds to Mayer et al.'s Group 1; similar values and patterns of normal (typical) ROM and normal EMG are seen for both. Laird et al.'s lumbar-dominant subgroup and Mayer et al.'s Group 2 share a similar normal (typical) FRR response and a larger lumbar than pelvic contribution to ROM. Laird et al.'s pelvic-dominant subgroup is similar to Mayer et al.'s Group 3 with an abnormal (atypical) FRR response and a larger pelvic than lumbar contribution to ROM. Finally, Laird et al.'s guarded subgroup and Mayer et al.'s Group 4 also show the least trunk ROM, the least FRR and greater lumbar than pelvic contribution to ROM. Although Mayer et al.'s study differed in many ways, with predefined groups, the inclusion of post-surgical patients and a different method and measurement device, the subsequent groups are sufficiently similar to those reported by Laird et al. (2018B) to provide preliminary mutual validation.

Table 6.3 A comparison of movement-based subgroup kinematic data from two studies

Laird subgroups compared with Mayer groups	Laird et al. (2018B)	Standard (n=35)	Lumbar-dominant (n=52)	Pelvic-dominant (n=34)	Guarded (n=19)
	Mayer et al. (2009)	Group 1 (n=9) Normal ROM and normal EMG (normal FRR)	Group 2 (n=33) Abnormal (small) ROM and normal EMG	Group 3 (n=2) Normal ROM and abnormal EMG (loss of FRR)	Group 4 (n=91 Abnormal ROM and abnormal EMG
Trunk ROM	**Laird et al**	111 ± 12	97 ± 17	89 ±16	77 ± 20
	Mayer et al	109 ± 6	83 ± 3	111 ± 6	63 ± 22
Lumbar ROM	**Laird et al**	51 ± 9	54 ± 10	30 ± 8.5	47 ± 14
	Mayer et al	56 ± 7	42 ± 7	46 ± 9	34 ± 11
Pelvic ROM	**Laird et al**	60 ± 11	44 ± 5	59 ± 15	31 ± 11
	Mayer et al	55 ± 8	35 ± 14.	64 ± 15	29 ± 16
FRR EMG scores	**Laird et al**	0.00 ± 0.00	0.04 ± 0.05	0.48 ± 0.50	0.72 ± 0.55
	Mayer et al	2.1 ± 0.7	2.0 ± 0.7	7.5 ± 2.3	16.2 ± 8.6

Also, comparison can be made between the patterns of data reported by Laird et al. (2018B) and those patterns described in texts or articles that were based on clinical observation. These comparisons have already been briefly discussed by Laird et al. (2018B, p. 16). The O'Sullivan classification system, now named 'Cognitive Functional Therapy' (Fersum, KV et al., 2012; O'Sullivan, P et al., 2018; O'Sullivan, P.B., 2005a; O'Sullivan, P. B., 2005) classifies patterns of impaired movement that have specific, matched types of interventions for each classified subgroup. '*Control impairments*' describe directional movements that appear to have full range but are painful (O'Sullivan, P. B., 2005, p. 247). A flexion control impairment would demonstrate a full range of trunk flexion that provoked pain, typically with a greater lumbar than pelvic contribution to ROM. People belonging to the 'standard' or 'lumbar-dominant' subgroups would have kinematic patterns that are consistent with this description. The O'Sulllivan classification system also describes an 'active extension' pattern, with over-active thoraco-lumbar extensors, and a greater pelvic compared to lumbar contribution (O'Sullivan, P.B., 2005a, p. 321), that would be consistent with Laird et al's (2018B) pelvic-dominant subgroup. The same classification system describes people who have 'movement impairments' (as opposed to control impairments) where 'guarding' and movement restriction is present in the direction of pain. A commonly seen pattern of painfully restricted flexion with reduced ROM, classified as a 'flexion *movement impairment*' would be consistent with Laird et al.'s (2018B) 'guarded' subgroup.

These similarities between the lumbo-pelvic kinematic patterns reported by Laird et al. (2018B), other studies on lumbo-pelvic kinematics, and movement classification systems based on clinical observation, demonstrate some consistency and add support to the notion that there are recognisable phenotypes of flexion movement.

6.5.   Sitting

The three sitting parameters (relative sitting position, range of sitting pelvic tilt, and the pelvic tilt ratio (formed by the amount of trunk movement divided by the amount of pelvic tilt movement)) did not differentiate between the four subgroups and were removed from subsequent analysis. Figure 6.6 shows the relatively low level of contribution of the three sitting parameters to the four-subgroup model ($r^2 < 4\%$ for each parameter).

Figure 6.6 Profile plot from Latent Class Analysis including sitting details
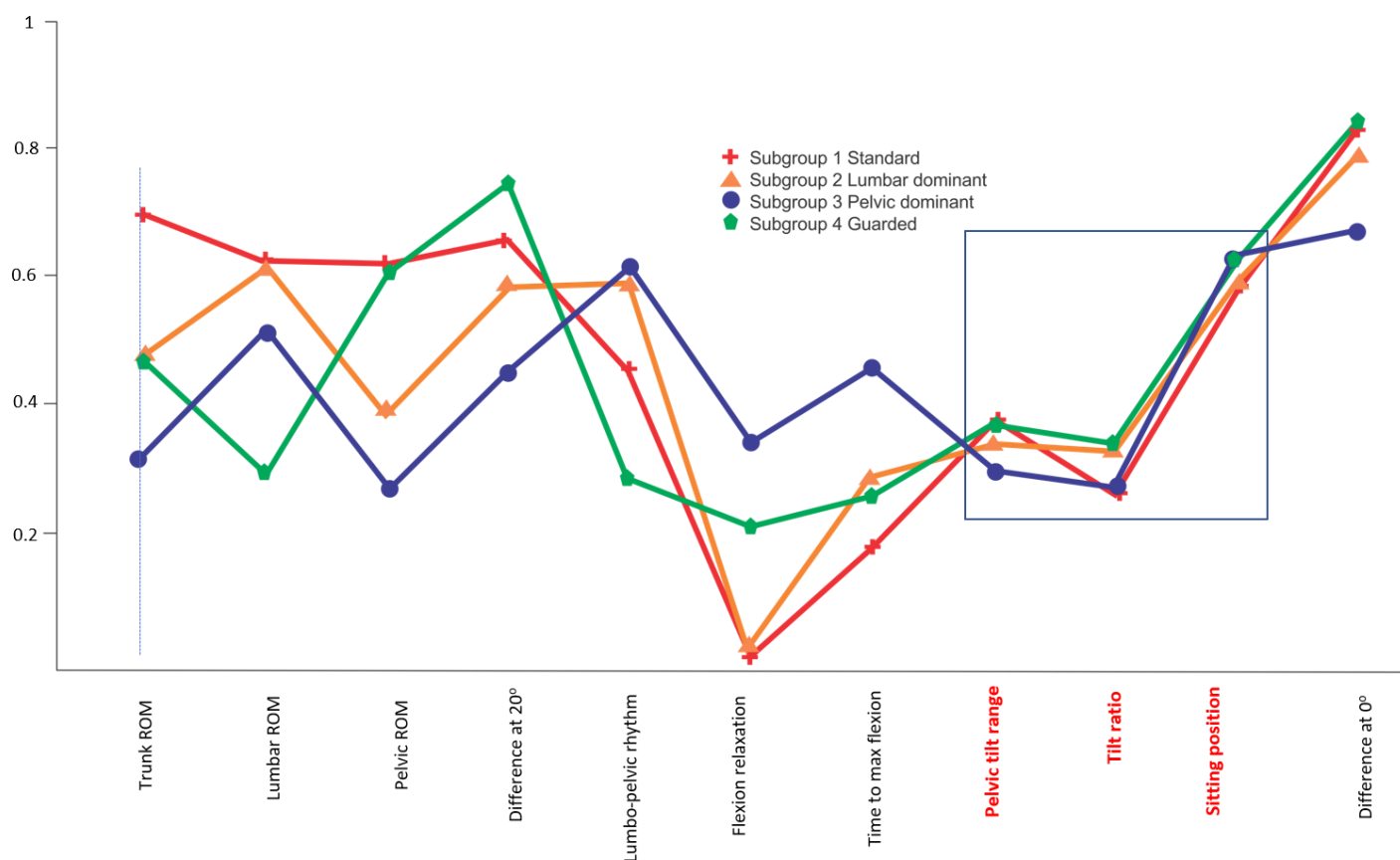
Figure 6.6 shows the inclusion of the three sitting variables (pelvic tilt range, tilt ratio and relative sitting position) outlined in the blue square. The Y axis displays a standardised mean score where the maximum value = 1 and the minimum value = 0.

It might have been expected that the lumbar-dominant subgroup would tend towards slump sitting. Similarly, the guarded and/or pelvic-dominant subgroups might have sat in a more upright position, had a smaller pelvic tilt range or used a trunk rather than pelvic pattern to replicate the pelvic tilt manoeuvre that they were asked to perform. Dankaerts et al. (2006) did find sitting-related differences between people with LBP who were pre-classified into 'flexion control impairment' and an 'active extension impairment' subgroup. They measured pelvic tilt, lower lumbar and upper lumbar angles during usual sitting in 33 people with persistent LBP and 34 control subjects. There was no difference between the LBP and control groups for any parameter without classification. However, when the LBP subjects were classified into 'flexion control' and 'active extension' control impairment subgroups, kinematic positional differences were seen. The active extension subgroup (which is similar to the

pelvic-dominant subgroup) sat with a greater forward sacral tilt, and greater extension at the lower and upper lumbar spine levels (a more lordotic position). The flexion control impairment group sat in a more slumped (kyphotic position) with a significantly different sacral and lower lumbar angle (absolute scores were reported graphically only). Those researchers also noted that the control group had a much larger difference (greater ROM) between usual and slumped sitting than either of the LBP subgroups at the sacral and lower lumbar levels. These findings indicated potential differences in kinematic sitting patterns for people with LBP when classified into movement-based subgroups, but these differences were not seen in the cohort investigated by Laird et al. (2018B). As sitting is commonly associated with LBP as an aggravating activity (Pengel, LHM et al., 2004; Suri, P et al., 2018), further investigation is required to validate or challenge findings.

6.6. The relationship of movement patterns to pain and activity limitation

In the study reported by Laird et al. (2018B), participants' pain intensity scores (measured with a Numerical Rating Scale) were very similar across the four subgroups. In contrast, activity limitation was statistically different between the standard and guarded subgroups (where the largest kinematic differences were also seen). The 'flexion aggravates, extension eases' questionnaire scores showed a similar pattern to the activity limitation scores. These results indicate that pain intensity alone did not discriminate between movement patterns.

Addressing how and why lumbar-dominant, pelvic -dominant or guarded patterns might be related to persistent LBP is speculative at this stage. It is biologically plausible that available ROM by itself is less important than how the available ROM is used in functional activities of daily living.

Hypermobility and excessive joint movement have been linked to injury development (Sahrmann, SA, 2011, p. 1) with *"the predisposition of a joint to move readily in a specific direction contributing to the development of a (maladaptive) movement pattern".* Applying this concept to the subgrouping classification, one could speculate that, in the ***'lumbar-dominant' subgroup***, biomechanical forces experienced during normal functional activities may be unequally absorbed by lumbar versus pelvic regions. A disproportionate amount of mechanical strain may be absorbed by the lumbar spine, due to its greater ROM and earlier than pelvic movement, with potentially less load shared by hip structures. Such a scenario might expose the lumbar spine to higher end-range strains and an increased risk of injury or irritation. Research designed to test this theory could improve our understanding of regional mechanics and consequences of shifts in forces associated with movement patterns.

Conversely (and again speculatively), a loss of movement (hypomobility) and generalised increased muscular activation of trunk muscles (increased co-contraction) have been reported in people with persistent LBP. This concept is consistent with the ***'pelvic-dominant' subgroup,*** where increased muscle activation of the lumbar extensors and markedly reduced lumbar ROM were seen. In this subgroup, flexion-related functional activities that require lumbar movement are likely to reach end-range lumbar movement earlier, with potentially elevated tensile and compressive forces. Higher biomechanical loads due to increased muscle activation and reduced lumbar ROM, might be associated with activities of daily living that would normally be assumed to be relatively easy. The activities may more easily create strain on potentially sensitised, inflamed and/or damaged spinal structures. Although beyond the scope of this thesis, there is biomechanical evidence (from finite modelling) of increased risk of injury when movement occurs at end-range intervertebral joint positions (Kuo, C-S et al., 2010; Schmidt, H et al., 2013; Schmidt, H et al., 2007; Schmidt, HP et al., 2007).

Although the relationship between the 'bio' and 'psycho-social' aspects of the biopsychosocial model were not explored by Laird et al (2018B), it would also be plausible to hypothesise that there may be variable associations between subgroups and psychological parameters, such as fear avoidance, psychological distress or poor self-efficacy (Crombez, G et al., 1999; Zale, E et al., 2013). For example, it would be useful to know if greater levels of fear avoidance were seen in people who presented with a 'guarded' pattern of movement. If subgroups of people with LBP have similar mean pain scores for each subgroup then movement differences between subgroups are not easily explained by pain (intensity) differences. For example, Thomas & France (2007) measured trunk, lumbar and pelvic ROM while performing a high, medium and low height reaching task (touching a target). They assessed the association between pain-related fear and ROM in 36 people with subacute LBP over a 12-week period (initial assessment at 3 weeks post-injury, then at 6 and 12 weeks). People were dichotomised to a high (n=18) or low (n=18) fear group. Pain scores were similar for the high and low fear groups, but the high fear group had greater activity limitation (p<.0001). The high fear group used significantly less lumbar movement when reaching/touching all three targets. The mean lumbar ROM used for each of the high (6°), medium (16°) and low targets (36°) was significantly less (p<.001) for the high fear group compared with the low fear group, despite similar pain intensity. The ROM used indicated that each task was unlikely to require end range movement. The authors argue that the reduced lumbar ROM used by the high fear group to achieve each of the three heights was "*striking because it cannot be explained as a simple matter of limited lumbar range of motion or lumbar flexibility* (Thomas, JS et al., 2008, p. E463)". The ROM differences

disappeared at 12 weeks as pain reduced. These results also support the notion that the method (pattern) of movement used in a functional task might be more important than the peak achievable ROM and that drivers of movement patterns may not only be physical.

6.7.   Summary

Four distinct flexion movement patterns were discernible based on clusters of lumbo-pelvic kinematic parameters. While these patterns were derived only from lumbo-pelvic kinematic parameters, they also overlap with similar descriptions of movement-based classification systems, as well as with other studies that have used kinematic assessments. These patterns may have potential implications for management and research which will be discussed in Chapter 7. If one considers a biopsychosocial model then further work could explore relationships between psychosocial factors and kinematic based subgroups.

7. Chapter 7 Summary of main findings and conclusions

7.1. Introduction and summary of findings

The relationship of movement to pain and activity limitation remains a research challenge despite the large volume of existing research (Costa, L et al., 2013). The main aim of the research in this thesis was to explore that relationship and the relevance of movement assessment for people with persistent LBP. Chapter 1 described the high prevalence rate of LBP, the significant economic and personal impact of LBP, and presented an argument for the merits of measuring movement in people with LBP. Chapters 2-6 are summarised briefly below (in 7.1.1 to 7.1.5).

7.1.1. Changes to movement patterns are infrequently measured and have an inconsistent association with improvements in pain and activity limitation (Chapter 2)

In Chapter 2, Laird et al. (2012) systematically reviewed what was known about changes to lumbo-pelvic movement, muscle activation or postural *patterns* in people with persistent LBP from randomised clinical trials of interventions. The review also examined if changes in a movement (or muscle activation) pattern were associated with changes in pain and/or activity limitation. Although movement-related interventions, such as exercise and functional retraining therapies, are recommended treatments for people with persistent LBP, the review found only 12 randomised clinical trials that measured both movement pattern-related parameters and pain/activity limitation before and after treatment. Those trials that did measure change in movement pattern parameters identified small, inconsistent changes in movement parameters associated with interventions, with little evidence of a relationship between changes in movement patterns and changes in pain or activity limitation.

7.1.2. People with persistent LBP do move differently from people without LBP (Chapter 3)

In Chapter 3, Laird et al. (2014) systematically reviewed what was known about differences in lumbo-pelvic kinematic parameters in people with and without persistent LBP. This second systematic review included a larger number of studies (n=43) that compared ROM, lumbo-pelvic rhythm, speed of movement, pelvic tilt position and proprioception parameters. The review concluded that, on average, people with persistent LBP have a smaller lumbar ROM, reduced proprioception and slower movement speed. While some parameters

were frequently compared, such as lumbar ROM, other parameters, such as pelvic ROM, pelvic tilt angle in sitting and standing and regional timing and sequence of movement, were less commonly examined. People with persistent LBP were also shown to have greater within-group variability for flexion, lateral flexion and rotation ROM scores. The review also highlighted the heterogeneous nature of available studies with respect to method design and quality, which prevented publishing data on normative movement or what might represent atypical movement outside of an expected range. None of the included studies used inertial motion sensors.

7.1.3. Lordosis, range of movement and lumbo-pelvic rhythm have different levels of consistency but have good to excellent reliability (Chapter 4)

The study reported in Chapter 4 (Laird, R et al., 2016), measured the consistency of lumbo-pelvic kinematic parameters in 63 people with and without LBP using a new type of measurement system based on inertial motion sensors. It reported that lumbo-pelvic kinematic parameters have a 'bandwidth' of expected variability which was defined by calculating minimal detectable change scores (with 90% confidence levels). The variability 'bandwidth' was smaller for within-session measurement and, as expected, larger when comparing between two tests on the same day or tests between days. This 'bandwidth' of variability represents a combination of biological variation and measurement error. Inter-tester and intra-tester reliability demonstrated good to excellent agreement for most comparisons.

7.1.4. Defining atypical movement then comparing the prevalence of atypical lumbo-pelvic kinematic parameters between people with and without persistent LBP (Chapter 5)

In Chapter 5, Laird et al. (2018A), measured and compared lumbo-pelvic kinematic parameters in 266 people with and without LBP using wireless sEMG and inertial motion sensors. Flexion-related lumbo-pelvic kinematic parameters were defined and then identified as atypical by using the 10th centile of the NoLBP group. A number of flexion-based lumbo-pelvic kinematic parameters were significantly more prevalent in the LBP group including small trunk, lumbar and pelvic ROM, slow movement speed, less FRR and delayed pelvic compared to lumbar regional movement. The other flexion-based lumbo-pelvic kinematic parameters such as sitting and lumbo-pelvic rhythm, were equally prevalent between groups. People with LBP who had atypically small lumbar and pelvic ROM had a significant association with pain when using a dichotomised 'high pain on bending' score.

7.1.5. People flex in differing ways (Chapter 6)

In Chapter 6, Laird et al. (2018B) used latent class analysis to determine if any patterns/subgroups of flexion-based lumbo-pelvic kinematic parameters could be identified in the cohort assessed by Laird et al. (21018A). Four different patterns/subgroups of flexion were described using clinically interpretable descriptions: 'standard', 'lumbar-dominant', 'pelvic-dominant' and 'guarded' subgroups. People without LBP were seen in three of the four subgroups, although almost 80% of these people were in the 'standard' subgroup. People with LBP were spread across all four subgroups. There were significant differences in most lumbo-pelvic kinematic parameters between many of the subgroup comparisons, indicating that the subgroups were relatively distinct. The presence of four flexion-related movement patterns adds strength to the concept that people move in different ways (different motor control patterns). There was no difference in pain intensity between subgroups when measured by a numerical rating scale but there were differences between subgroups for activity limitation and a pain-related 'flexion aggravates, extension eases' questionnaire score.

7.2. A summary of the contributions and new knowledge from original research within this thesis

Table 7.1 tabulates the main research questions asked in each review/study, with a brief indication of how the results of each review/study provide new insight into what was previously known about lumbo-pelvic movement in people with and without LBP.

Table 7.1 A summary of research questions asked and the contributions made by each paper

Research question		What was known before	The findings of this research
Chapter 2			
2a	Can interventions for LBP successfully change patterns of muscle activation, movement or posture?	Unknown.	The review found small and inconsistent effects for movement-based interventions that aimed to change muscle activation, flexion relaxation and postural patterns.
2b	If so, are improvements to movement parameters associated with reduced pain and activity limitation?	Unknown.	Only infrequent and inconsistent associations between changes in muscle activation, flexion relaxation or posture and improvements in pain/activity limitation were seen
Chapter 3			
3a	Which lumbo-pelvic kinematic parameters have been used to compare people with and without LBP?	A large number of studies report comparisons of various lumbo-pelvic kinematic parameters between people with and without LBP. Reported differences vary between studies. Until this review, there had been no systematic review of parameters that had been compared, nor any that synthesized comparison of lumbo-pelvic kinematic parameters for those with and without LBP.	The review found that lordosis angle, ROM (mostly lumbar ROM), lumbo-pelvic rhythm, speed, proprioception and pelvic tilt angle were used to compare people with and without LBP. Although some parameters, such as lumbar ROM were measured frequently, other parameters were less commonly assessed.
3b	What are the reported differences in lumbo-pelvic kinematic parameters when comparing people with and without persistent LBP?	No meta-analysis of any reported differences in lumbo-pelvic kinematic parameters had been performed, so the overview of lumbo-pelvic	On average, people with LBP have reduced lumbar ROM and proprioception, and move more slowly compared with people without LBP. No differences were seen for lordosis angle, lumbo-pelvic rhythm or standing pelvic tilt angle.

		kinematic differences between people with and without LBP remained unclear.	
3c	Is there a difference in the variability of lumbo-pelvic kinematic parameters for people with and without LBP?	Unknown.	Movement variability was greater for people with LBP for flexion, lateral flexion and rotation ROM, and movement speed, but not for other lumbo-pelvic kinematic parameters.
3d*	Can reported differences in lumbo-pelvic kinematic parameters guide clinicians in identifying typical and atypical movement?	Normative data have been published for some but not all parameters. However, reported values for parameters differ widely between studies.	There was wide divergence in method, device and sample definition that prevented describing mean values for each parameter derived from a meta-analysis. While a clinician who uses the same method and instrument to that used in individual studies might compare their values to normative data, however, synthesising normative data from meta-analysis is likely to be a misleading guide to normative data.
Chapter 4			
4a	How consistent are repeated measures of lumbo-pelvic kinematic parameters during within-session use?	Unknown.	Lumbo-pelvic kinematic parameters showed within-session consistency of 5° or less for all ROM parameters when comparing repetitions of movement using the metric of minimal detectable change (at 90% confidence levels).
4b	How much change is required to be confident of true within-session change when using inertial motion sensors?	Unknown	Changes would need to exceed 2°–5° for ROM components, and 3-4 % of lumbar contribution to lumbo-pelvic rhythm, for 90% confidence that movements had actually changed.

4c	How much change is required to be confident of true between-session change when using inertial motion sensors?	Unknown.	Changes would need to exceed 10°–15° for lumbar lordosis, 5°–15° for ROM components, and 8–15 % of lumbar contribution to lumbo-pelvic rhythm, for 90% confidence that movements had actually changed.
4d*	Which ROM differences were seen between people with and without LBP in this small sample (n=62)?	No previous papers compared lumbo-pelvic kinematic parameters in people with and without LBP using wireless inertial motion sensors.	There were few ROM differences between people with and without LBP, with the LBP group showing larger flexion pelvic ROM, reduced right lateral flexion lumbar ROM, and reduced percentage contribution of lumbar versus pelvic contribution to flexion.
Chapter 5			
5a	What differences exist when comparing flexion- related lumbo-pelvic kinematic parameters (including sitting) in people with and without persistent LBP when measured with wireless motion and EMG sensors in a large sample (n=266)?	Laird et al. (2014) reported lumbo-pelvic kinematic parameter differences in people with and without persistent LBP but found no studies that used wireless inertial motion sensors. The study by Laird et al. (2016) found few differences in a small sample.	Significant movement differences during flexion were seen in people with LBP, with significantly less trunk, lumbar and pelvic ROM, slower movement, delayed pelvic movement and greater lumbar extensor muscle activation, but without differences for any sitting parameter or lumbo-pelvic rhythm.
5b	What is the prevalence of atypical lumbo-pelvic kinematic parameters in people with and without persistent LBP and are there differences?	Unknown.	Atypical movement was significantly more prevalent in the LBP group for small trunk (5.4 times more prevalent), lumbar (3 times more prevalent) and pelvic ROM (3.9 times more prevalent), low FRR (4.9 times more prevalent), delayed pelvic motion at 20° flexion (2.9 times more prevalent), and longer movement duration (4.7 times more prevalent).

5c*	Are atypical lumbo-pelvic kinematic parameters associated with pain or activity limitation?	There are conflicting reports with contradictory findings of associations of lumbo-pelvic kinematic parameters (particularly ROM) with pain and activity limitation.	High 'pain-on-bending' intensity was significantly associated with small lumbar ROM and pelvic ROM. All other parameters were not significantly associated with pain.
Chapter 6			
6a	Are there relationships between lumbo-pelvic kinematic parameters that form patterns (subgroups), and if so, are these patterns clinically recognisable?	Unknown. Although clinicians have developed classification systems based on movement-related differences, there is no data-driven research that has specifically looked for patterns of movement using lumbo-pelvic kinematic parameters.	Four subgroups with high probabilities of participant membership were found indicating relatively distinct patterns of movement. These subgroups were described as standard, lumbar dominant, pelvic-dominant and guarded patterns.
6b	Are these subgroups equally seen within both NoLBP and LBP populations?	Unknown.	People with and without LBP were not equally distributed amongst subgroups. People without persistent LBP were seen in three of the four subgroups, although almost 80% of the NoLBP group were found in the standard subgroup. People with LBP were found in all four subgroups.
6c	How do any subgroups differ?	Unknown.	The standard subgroup had the greatest range of trunk flexion, fastest movement, full flexion relaxation, and synchronous lumbar versus pelvic movement. The lumbar dominant subgroup had the greatest lumbar ROM, less flexion relaxation, and a 0.9 sec lag of pelvic movement. The pelvic-dominant subgroup had the smallest lumbar ROM, a 0.6 sec delay of lumbar movement (compared

			with pelvic movement), and less flexion relaxation than the lumbar-dominant subgroup. The guarded subgroup had the least flexion relaxation, slowest movement, greatest delay of pelvic movement and the smallest pelvic ROM.
6d	Is there any relationship of pain and activity limitation with any subgroups found?	Unknown.	There was greater direction-specific ('flexion aggravates, extension eases') pain and activity limitation scores for the guarded subgroup compared with the other three subgroups, and a greater percentage of people with leg pain in the lumbar-dominant and guarded subgroups.

These questions were either secondary to the main aim, or arose as a result of the findings of the review/study

236

7.3. Research methodology – reflections on the strengths and weaknesses of the studies in this thesis

7.3.1. Randomised controlled trials have strengths but also have limitations

One of the strengths of the review reported in Laird et al. (2012) was that it only included randomised controlled trials, as these compare the effects of an intervention with something else (control or alternative intervention) and their inherent randomisation uniquely controls for some sources of bias. However, a randomised controlled trial is designed to compare the directional relationship of group means, but group-level results do not provide information on which individuals are more responsive to the intervention, or why people might respond, unless mediation analysis is included. The inclusion of non-RCTs in Laird et al., (2012) may have uncovered other types of studies in which the association between movement pattern change scores and pain/activity change scores was investigated.

Study designs such as multiple single-case experimental designs or case-control studies can measure if movement-based interventions change movement and if any changes are associated with changes to pain/activity limitation (Morley, S et al., 2015). There are differing levels of rigour in this type of report varying from case reports that have limited methodological design strength to stronger, multiple 'N=1' single-case experimental design studies that conform to the criteria described by Kratchowill et al. (2010). Dankaerts et al. (2007) published a detailed case-control study comparing one person with persistent LBP to a pain-free control person. The authors used visual observation of quality of movement and measurements of lumbar ROM, EMG activity of lumbar extensor and transverse abdominal wall muscles. They noted that the 'case' person demonstrated physical changes following eight sessions of Cognitive Functional Therapy. Observed changes included a more consistent lumbar contribution to flexion (but with no difference in the maximum lumbar ROM pre versus post intervention), improved flexion relaxation and normalisation of transverse wall EMG activity, accompanied by improvements in pain and activity limitation. Although that case-control study (Dankaerts, W. et al., 2006f) provides evidence that physical changes can occur on an individualised basis, it did not include any repeated baseline measurements or report the sequence/pattern of changes in any outcome over the eight sessions; these details would assist in providing evidence of a causal relationship (Kratchochwill, T et al., 2010). In contrast, Wand et al. (2011) used a robust, single case experimental design study, with repeated baseline

measurements, and differing delays in when the intervention was initiated, in three people with persistent LBP. Wand et al reported improvements in pain and activity limitation following a sensorimotor intervention but did not report measurement of physical outcomes. So, the relationship between changes in movement and changes in pain/activity limitation could be investigated by reviewing studies that utilise other types of experimental designs, as well as randomised controlled trials. Ultimately effects of interventions are best tested with an RCT, but the temporal relationships between specific events on the path to movement, pain or function change might be illuminated with well conducted single case studies.

7.3.2.   Longitudinal studies are required to observe any relationship between changes in movement and changes in pain/activity limitation

The findings from single case experimental designs may help to inform trial design by identifying which movement-related parameters have sufficient strength of relationship with activity limitation/pain to warrant further investigation with a randomised controlled trial. This thesis used cross-sectional data in Chapters 3, 5 and 6 with the intent of exploring which parameters had been investigated, if differences existed between LBP and NoLBP groups, the prevalence of movement differences and patterns of relationship between movement parameters. However, cross-sectional data cannot be used to infer any causal relationships. Further research would need to consider longitudinal studies, such as single case experimental designs, case-control, cohort studies or larger randomised controlled trials to provide information on the 'cause-versus-consequence' relationship of lumbo-pelvic kinematic parameters to LBP.

7.3.3.   Is looking at flexion enough to establish that subgroups are seen in people with persistent LBP?

Only flexion-related lumbo-pelvic kinematic parameters were considered by Laird et al. (2018A and 2018B). A discussion on why the investigation was limited to flexion-related parameters is included in the papers. However, although the presence of subgroups of flexion-related lumbo-pelvic kinematic parameters was established by Laird et al. (2018B), this work represents only a part of what would need to occur before one could have strong confidence in defining movement-related phenotypes in people with persistent LBP. Further study should include analysis of lumbo-pelvic kinematics in other directions of movement. It could also include other movement-related parameters, such as peak strength/endurance of abdominal, lumbar and hip muscles, and

other muscle activation patterns e.g. deep versus superficial muscle activation, and proprioception accuracy. If movement-based phenotypes can be established, then additional information about parameters from other psychosocial dimensions such as cognitions (e.g. fear avoidance, self-efficacy), and emotions (e.g. anxiety, depression) might provide insight into relationships between movement and psychological factors. Consideration of how this might occur is discussed in section 7.4.

7.4. Implications for future research and future research directions

7.4.1. Choosing movement parameters to measure as outcome variables

The prevalence of atypical lumbo-pelvic kinematic parameters is highly likely to vary between samples. The most prevalent atypical parameter in this cohort was atypical FRR (seen in 52% of people), followed by small trunk ROM (48%), slow trunk movement (47%), small pelvic ROM (34%) and small lumbar ROM (29%). If one were to choose lumbar ROM as the measure of physical impairment, then, at least for this cohort, less than a third of people with persistent LBP would have movement that is outside of an expected 'typical' ROM. If a study intends to investigate changes to lumbo-pelvic kinematic parameters, statistical evaluation would ideally take the prevalence rate into consideration to avoid a washout effect of results. Choosing a single atypical parameter for group comparisons may be less useful when only a percentage of people have atypical movement. An alternative approach might be to use an individualised 'patient-specific *movement* scale' where one or more atypical movement parameters are identified on an individual basis and monitored for change over the period of an intervention. This approach is similar to the use of a 'patient-specific functional scale' (Westaway, M et al., 1988).

7.4.2. Replication studies are required to test the generalisability of these findings

Although the results reported by Laird et al. (2018A and (2018B) have potential importance in identifying atypical movement and movement-based subgroups of people with persistent LBP, replication studies are required to determine the validity and generalisability of these findings (KNAW, 2018). A replication study can determine if the results are reproducible, and if so, adds confidence for generalisability. Although a replication study needs to closely emulate the methodology of the existing study, it also has the opportunity to improve and extend the

strategy of data collection and analysis, e.g. additional directions of movements could be assessed, psychological parameters recorded, and/or a longitudinal element added.

7.4.3. Inconsistent results seen between studies may be affected by movement heterogeneity

Current guidelines on managing persistent LBP suggest that exercise is appropriate but inconsistent results between trials prevent recommendations about which type of exercise is best (see section 2.1.1, p.27). There is a range of opinions as to why inconsistent results are seen across studies of interventions for LBP. However, the considerable heterogeneity seen in people with persistent LBP across and within dimensions is thought to contribute to differing results (Costa, L et al., 2013; Hancock, MJ et al., 2016). Hancock and Hill (2016, p. 319) write *"We debate and investigate the best type of exercise; however, without a strong understanding of the underlying causes (phenotypes) and hypothesized treatment targets, it is difficult to empirically test for whom an intervention may work best and how it may work. Arguably, there is a need to stop conducting more clinical trials for a condition that we don't really understand, using interventions for which we don't have a strong rationale, and to put more effort into better understanding the different causes of and types of patients with LBP and the mechanisms of the interventions available."*

The findings by Laird et al. (2018B) demonstrated that, at least for flexion movement, and in this cohort of people, differing movement patterns appear in clusters of lumbo-pelvic kinematic parameters. These subgroups may represent or contribute to phenotypes within the movement dimension of LBP, although this is speculative at this stage. The validation of movement-related phenotypes would need both replication, and further investigation to include other movements. Although also speculative, it is plausible that these different subgroups could have variable responses to any given intervention. If the presence of subgroups based on differing patterns of movement is confirmed, these results may assist in explaining inconsistent results from trials of interventions for LBP.

7.4.4. Movement parameters or patterns may predict different outcomes or contribute to pain

Movement-based subgroups or single atypical lumbo-pelvic kinematic parameters may act as treatment effect moderators, where an atypical movement or subgroup type might predict which person is likely to respond to a

particular movement intervention. These subgroups or atypical movements may also act as mediator variables that are amenable to intervention and contribute to a causal relationship between LBP and activity limitation.

7.4.5. Do people have atypical movement at baseline in longitudinal studies?

If the relationship of movement to LBP is being investigated, it would be important to know how many people have a deficit in the particular 'movement outcome of interest' at baseline. It is logical that people who have a deficit at baseline are more likely to be responsive to a movement-based intervention than those who have typical/normal movement at baseline.

An example of this concept could be applied to the four trials (five studies) included in Laird et al (2012) that measured FRR (Lalanne, K et al., 2009; Mannion, AF et al., 2001a; Mannion, AF et al., 1999b; Marshall, P et al., 2006; Ritvanen, T et al., 2007). None of the trials attempted to identify the percentage of people in each group with an abnormal FRR response, as only group means were reported. Unlike ROM, identifying abnormal (atypical) FRR is relatively simple, with any electrical activity seen in the full flexion phase recognised as atypical. Without knowledge of the percentage of the LBP subjects who had atypical FRR, it is not possible to know if the groups were equally likely to be responsive to an intervention that aims to rectify FRR abnormalities. If one group had 25% of people with atypical FRR, while the other group had 75% of people with atypical relaxation, the treatment outcomes are likely to be confusing. It would also be important to know if individuals who had low FRR showed changes to the FRR across time or in response to an intervention and if that change was associated with changes in pain/activity limitation.

7.4.6. Future research directions

Among the findings of this thesis, two key elements warrant further investigation: (1) the utility of knowledge of atypical movement, and, (2) defining movement-related subgroups of people with LBP.

There are a number of strategies and directions that could extend the research undertaken in this thesis:

1. As previously discussed, knowledge of other lumbo-pelvic kinematic parameters such as extension, lateral flexion, and rotation, would add to the definitions of atypical movement and contribute to further developing and clarifying the nature of movement-based phenotypes.

2. If clinicians are to have confidence in using atypical movement definitions, or identifying different movement-based subgroups, replication studies with other samples of people with and without LBP would be required. These replication studies could also test the stability of cut-points used by Laird et al. (2018A). Further research could investigate if using the 10th centile is appropriate, and if this method is equally useful for all parameters. For example, a 10th centile approach may not be equally useful for FRR as it may be for ROM.

3. If a new cohort is studied, further information could be gathered. Latent class analysis could analyse if the inclusion of lumbo-pelvic kinematic parameters of other movement directions adds clarity or complexity to movement-based subgroups found by Laird et al. (2018B). Data could be added to the existing subgroup analysis by maintaining the four flexion-based subgroup definitions. There are alternate methods of adding further data. All parameters could return to their independent status and be re-analysed. Alternatively, subgroups could be independently analysed in each cardinal plane i.e. all flexion data, followed by a separate analysis for all extension data, then all lateral flexion data and the composite results subsequently synthesised using similar methods.

4. It would be useful to see if any relationships between other movement-related parameters such as strength, endurance, muscle activation patterns and proprioception align with currently identified subgroups or if these parameters create different patterns. If more complex movement subgroups are discernible, then testing for relationships between psychological factors and subgroups would also be of interest.

5. The most important step would be a longitudinal study that investigates the relationship between changes in movement and changes in pain/activity limitation when assessed with wireless inertial motion and sEMG sensors. Such an approach would require a sample size sufficient to cope with parameters that are only seen in a percentage of people with persistent LBP, and ideally would be part of a randomised controlled trial. Measurements would be required at baseline and throughout the trial period as a minimum. A current project, an Australian government, NHMRC-funded clinical trial (the RESTORE trial) has commenced and may meet some of these aims.

6. Another less complex method that could assess the relationship of changes in movement and changes in pain/activity limitation might be to use a case-control approach, or multiple single case experimental design studies. This approach would specifically include subjects who have either predefined 'atypical'

movement or are classified into a movement-based subgroup as described by Laird et al. (2018B). An intervention would be applied that is specifically intended to change the movement parameter(s) of interest, with measurements of movements would be repeated over time. If an N=1 design is used, then a sequence of baseline measurements preceding the intervention would help to determine if the start of the intervention is aligned with any changes in movement and/or pain/activity limitation, as opposed to changes that might spontaneously occur over time. If a number of N=1 cases are measured, then varying the number of baseline measurements (the randomised baseline approach) would also help to distinguish between changes that occur due to the intervention and changes that occur for other reasons. This approach is likely to provide some clarity about the ability of an intervention to change a specific parameter and better describe the relationship between the movement parameter and pain. A third and more complex method may be to categorise people into groups based on patterns/subgroups seen by Laird et al. (2018B), apply an intervention and observe baseline, through-intervention and end-of-intervention changes and determine which groups demonstrate movement and/or activity limitation changes in response to the intervention.

7.5.   Clinical use of motion sensors

Motion and sEMG sensors can measure movement and identify lumbo-pelvic kinematic parameters that are unlikely to be accurately observed by visual estimates alone. Confident identification of simple angular inclination and muscle activation patterns, such as the FRR, timing and sequence of regional movement, and composite subgroups of clusters of lumbo-pelvic kinematic parameters (such as those reported in Chapter 6) are likely to require the assistance of technology. The difference seen in movements of people with and without pain suggests that detecting atypical movement is potentially important

Motion sensors may be useful in identifying and monitoring changes in movement. Monitoring changes in movement may help guide treatment choice by clarifying which changes in movement occur and how any changes in movement are (or are not) accompanied by changes in pain/activity limitation. If within-session changes are used to guide treatment choice, then using technology to identify change may be helpful.

Motion sensors can assist in identifying subgroups of people with persistent LBP. Clinicians typically think that there are subgroups of people with persistent LBP but there is little agreement about the nature of these subgroups. There is evidence of clinicians being able to reliably identify classification system-based subgroups

(Dankaerts, W. et al., 2006d; Harris-Hayes, M et al., 2009; Henry, SM et al., 2012; Trudelle-Jackson, E et al., 2008; Vibe Fersum, K et al., 2008; Widerstrom, B et al., 2012). However, there is little agreement about the definition of these subgroups nor the type of therapeutic intervention(s) that are most useful. It may be that using inertial motion sensors or other technologies can increase the reliability of distinguishing movement-based subgroups, although this remains to be tested. There is early evidence that identifying movement-based subgroups of people with persistent pain is useful therapeutically (Fersum, KV et al., 2012). The subgroups identified by Laird et al. (2018B) are potentially useful but need to be viewed as preliminary work with caution against over-estimating the clinical value of these patterns until further research into the validity and potential benefits of the identified subgroups occurs.

Using motion and EMG sensors may also have a therapeutic role through the use of movement-based biofeedback to reduce pain and activity limitation. Biofeedback to improve human performance has proven useful in a number of physiological (neuromuscular, cardiovascular and respiratory systems) and biomechanical (movement, postural control and force generation) dimensions (Giggins, OM et al., 2013). There is early evidence that changing aspects of movement and posture in people with LBP (Kent, P et al., 2015a) using movement and postural biofeedback can improve pain and activity limitation outcomes. The use of inertial motion sensors has advantages of being small, wireless, can monitor movement within both clinic and real-world environments and communicate information directly to users and clinicians. Although further research is required before one could have confidence in the therapeutic advantage of motion sensor-driven biofeedback for people with LBP, the possibilities are intriguing.

8.   Thesis conclusion

This thesis examined the relevance of measuring lumbo-pelvic movement in people with and without LBP. Lumbo-pelvic movement has been challenged as being unimportant, and perhaps irrelevant, with inconsistent results from trials that attempt to change movement parameters, and little relationship seen between restoring movement and improvements in pain or activity limitation. However, significant movement differences between people with and without LBP were demonstrated in a meta-analysis of comparative studies, and in a new body of work that used wireless inertial motion and EMG sensors to investigate lumbo-pelvic kinematic parameters. A novel method of assessing and distinguishing between expected, typical movement and atypical movement was developed, revealing a wide range of atypical movements, some that were significantly more prevalent in people with LBP. Distinguishing atypical from typical movement parameters reflects clinical practice, is common to other areas of medicine, and could guide further LBP research design and directions. This thesis continued by investigating if any relationships existed between lumbo-pelvic parameters. Analysis revealed four recognisable patterns/subgroups of flexion-related movement in people with and without LBP, but in an unequal distribution. Identifying that people have differing movement patterns is a potentially important step towards guiding how treatment might match individual needs. The differences in movement patterns and the greater prevalence of atypical movement in people with LBP compared with people without LBP, support the concept that lumbo-pelvic movement may have relevance to treatment choices for people with LBP. Measuring movement is likely to help unravel the complex cause-versus-consequence relationship between LBP and movement.

This new window of investigation into the lumbo-pelvic movements of people with persistent LBP provides new direction and hope for improved diagnosis and treatment in a field where little has improved for many decades. Validation, criticism and advancement of this line of enquiry can only serve to progress our understanding and ability to support those who suffer LBP.

9. Appendices

9.1.   Appendix A: Laird et al (2012) PDF version

BMC
Musculoskeletal Disorders

RESEARCH ARTICLE

Open Access

Modifying patterns of movement in people with low back pain – does it help? A systematic review

Robert A Laird[1,3*], Peter Kent[2] and Jennifer L Keating[1]

Abstract

Background: Physiotherapy for people with low back pain frequently includes assessment and modification of lumbo-pelvic movement. Interventions commonly aim to restore normal movement and thereby reduce pain and improve activity limitation. The objective of this systematic review was to investigate: (i) the effect of movement-based interventions on movement patterns (muscle activation, lumbo-pelvic kinematics or postural patterns) of people with low back pain (LBP), and (ii) the relationship between changes in movement patterns and subsequent changes in pain and activity limitation.

Methods: MEDLINE, Cochrane Central, EMBASE, AMI, CINAHL, Scopus, AMED, ISI Web of Science were searched from inception until January 2012. Randomised controlled trials or controlled clinical trials of people with LBP were eligible for inclusion. The intervention must have been designed to influence (i) muscle activity patterns, (ii) lumbo-pelvic kinematic patterns or (iii) postural patterns, and included measurement of such deficits before and after treatment, to allow determination of the success of the intervention on the lumbo-pelvic movement. Twelve trials (25% of retrieved studies) met the inclusion criteria. Two reviewers independently identified, assessed and extracted data. The PEDro scale was used to assess method quality. Intervention effects were described using standardised differences between group means and 95% confidence intervals.

Results: The included trials showed inconsistent, mostly small to moderate intervention effects on targeted movement patterns. There was considerable heterogeneity in trial design, intervention type and outcome measures. A relationship between changes to movement patterns and improvements in pain or activity limitation was observed in one of six studies on muscle activation patterns, one of four studies that examined the flexion relaxation response pattern and in two of three studies that assessed lumbo-pelvic kinematics or postural characteristics.

Conclusions: Movement-based interventions were infrequently effective for changing observable movement patterns. A relationship between changes in movement patterns and improvement in pain or activity limitation was also infrequently observed. No independent studies confirm any observed relationships. Challenges for future research include defining best methods for measuring (i) movement aberrations, (ii) improvements in movements, and (iii) the relationship between changes in how people move and associated changes in other health indicators such as activity limitation.

Keywords: Low back pain, Movement disorders, Randomized controlled trial, Exercise therapy, Posture

* Correspondence: robert.laird@monash.edu
[1]Department of Physiotherapy, Monash University, PO Box 527, Frankston, Victoria 3199, Australia
[3]Postal Address: 7 Kerry Rd, Warranwood, Melbourne, Victoria 3134, Australia
Full list of author information is available at the end of the article

BioMed Central

Background

The causes of low back pain (LBP) appear to be complex and multifactorial, with both biological and psychosocial components associated with chronicity [1,2]. While numerous patho-anatomic structures have been associated with LBP, it is often difficult to establish a definitive anatomical cause or initiating factor for LBP in individual people [3,4]. Furthermore, although the pathogenesis of LBP has also been associated with genetic causes [5], such influences are not readily modifiable. In daily practice, many clinicians observe and treat physical impairments ranging from postural anomalies [6,7], localised intervertebral kinetic disturbance [8], motor control disturbance [9,10], muscle imbalance [11] and muscle atrophy [12].

People with persistent (chronic) or recurrent LBP have been variably reported to exhibit movement pattern aberrations such as increased trunk stiffness [9,13], poor proprioception [14], altered patterns of activation of abdominal muscles [10,15], extensor muscles [16-18], and postural dysfunction [19-21]. Different patterns of lumbo-pelvic kinematics during activities such as forward bending and sit-to-stand have been demonstrated in studies comparing people with and without LBP [22-25]. Methods for measuring lumbo-pelvic movement patterns can by categorised into three broad target groups: (i) muscle activity patterns, for example the contribution of deep versus superficial trunk muscles, (ii) patterns of hip to lumbar kinematics, for example the relative contributions of hip joint compared with lumbar spine movement to specific activities such as forward bending or walking, and (iii) postural patterns, for example slumped sitting compared with upright sitting posture.

Numerous interventions have targeted movement pattern aberrations associated with chronic LBP [10,26-29]. Some exercise interventions involve whole body movements such as aerobic exercise, Pilates, and yoga, while others target the activity of specific muscles. The effectiveness of exercise for LBP appears modest and not consistently associated with any particular form of exercise [30-32]. No consistent differences in LBP outcomes have been observed for highly individualised exercise programs that aim to alter lumbo-pelvic kinematics or postural patterns such as those based on the Alexander Technique [33,34], the Feldenkrais Method [33] or Pilates [35] compared with non-specific exercise. Similarly, reviews of interventions designed to alter patterns of specific muscle activity, variably described as motor control, trunk stabilisation or core stabilising exercise, have concluded little difference between outcomes achieved with motor control exercise compared with general exercise regimens [36-40]. As there is no standardisation in the reporting of exercise type, intensity, duration or frequency, one possibility is that some exercises are effective, but when trial outcomes are pooled, method heterogeneity in included studies precludes identification of trial-specific effectiveness.

Movement pattern aberrations associated with LBP, such as deviation from the normal activation patterns of Transversus Abdominus (TA) [10,41] have been reported. However the effect of interventions on these aberrant movement deficits has not been systematically evaluated. While most trials report effects on pain or activity limitation, few have measured changes in movement or postural patterns. This is reflected in five recent systematic reviews on the effectiveness of stabilisation ('motor control') exercises for LBP [36-40], which collectively synthesised 26 randomised controlled trials. More than half of the included trials in these reviews [36-40] used outcome measures of pain and activity limitation without measurement of any movement characteristic. Only three of 26 trials measured the effect of the intervention on a specific movement pattern aberration. As few trials measure movement pattern aberrations, this leaves three fundamental questions unanswered by existing reviews: (i) were movement pattern aberrations actually present in trial participants who received interventions designed to remedy these deficits? (ii) did the intervention achieve the intention of changing the movement pattern? and (iii) were improvements in other health parameters such as pain and activity limitation related to changes in movements classified as aberrant? To understand whether treatment can change movement pattern aberration, measurement of such deficits should occur before and after treatment, and the outcomes compared with those of a control group.

Aims of this review

The first aim of this systematic review was to determine the effect of movement-based interventions on movement patterns defined as physical measures of muscle activation, lumbo-pelvic kinematics or postural patterns in adults with LBP. The second aim was to examine the relationship between changes in movement patterns and subsequent changes in pain and activity limitation.

Methods

Data sources

Eight electronic databases (MEDLINE, Cochrane CENTRAL, EMBASE, AMI, CINAHL, Scopus, AMED, ISI Web of Science) were searched from inception until January 2012 using a sensitive search strategy based on that recommended by the Cochrane Collaboration (included as an Additional File). The search yield was initially screened for eligibility by one reviewer (RL) on title and abstract to remove duplicates and clearly

unrelated articles. A more detailed screening on title and abstract, and subsequently on retrieved full text articles, was performed independently by two reviewers (RL and PK). Disagreements were resolved by discussion. The protocol for this review has not previously been registered or published.

Study selection: inclusion and exclusion criteria

Trials were included if they were randomised controlled trials or controlled clinical trials that only contained participants with lumbo-pelvic pain (+/− leg pain) in both the intervention and control groups. The intervention must have been specifically designed to influence any one of three observable patterns of movement: (i) muscle activity patterns, (ii) lumbo-pelvic kinematic patterns or (iii) postural patterns. To be as inclusive as possible, no restrictions were placed on the duration of complaint or pain location. Full inclusion details of each study are provided in Additional file 1: Appendix 1. Exclusion criteria were trials of animals, of drug interventions and trials that included people who were pregnant or had spinal malignancy, infection, fracture, cauda equina syndrome, metabolic or spinal inflammatory disorders.

Types of outcome measures

For trials to be included, pre- and post-intervention data that quantified baseline measures and the effect on the target movement pattern relative to control measurements must have been reported. In the absence of these data, it could not be determined if the intervention was effective in changing the physical parameter it was designed to influence. These data were also required to investigate the relationship between change in movement patterns and change in health outcomes (pain and activity limitation). Acceptable methods for assessing movement patterns included any measures of specific muscle activation (eg timing of contraction, cross-sectional area, muscle thickness, electromyographic activity, ultrasound or other imaging measurement), lumbo-pelvic kinematics (eg a change in sequence, timing or coordination of movements such as lumbar versus hip contribution during lifting, sit-to-stand, forward bending) and any measures of sustained positions/postures of the lumbo-pelvic region (eg analysis of spinal kinematics within specified activities such as standing, sitting or sustained bending). Data must have been provided that described movement patterns (e.g. hip versus lumbar range, deep versus superficial muscle activity, particular sequences of timing, electrical activity or movement etc.).

Exclusion criteria at the level of outcome type were trials with outcomes that described only global range of movement or global measures of strength (eg trunk extension range or strength only), or trials that did not include data that enabled estimates of change in pain or activity limitation. This was because we considered that global range or strength were not surrogate measures of how the body coordinates movement patterns.

Data extraction

From all included papers, two assessors independently extracted the following data: compliance with review inclusion criteria, type and duration of intervention for experimental and comparison groups, number and type of participants, the targeted movement characteristic (muscle activity pattern, lumbo-pelvic kinematic pattern or postural pattern), pre- and post-intervention outcome measurements and their method of measurement. Data extracted by these reviewers (RL and PK) were checked for concordance and where differences occurred, a third reviewer (JK) cross-checked data with consensus reached by discussion.

Assessment of method quality

The PEDro scale was applied to assess potential sources of bias in included studies [42]. The PEDro scale has been reported as being adequately reliable [43] and valid [44]. Each clinical trial with a quality rating score on the PEDro website (http://www.pedro.org.au) has been independently assessed by two raters trained to assess method quality. Therefore where available, we used the quality scores from the PEDro website for included trials. There were two trials (reported in three papers) where scores were not available [45-47] and these were independently assessed (RL and PK) using the same PEDro scale and decision rules.

Data synthesis and analysis

Study details (inclusion/exclusion criteria, intervention and comparison treatments and outcome measure details) were extracted and summarized (see Additional file 1: Appendix 2). Means and standard deviations (SDs) for intervention and control groups, for each comparison, at each reported outcome period and for all three categories of outcome variables (movement pattern, pain, activity limitation) were entered into Revman (v5) software [48]. This software was used to calculate standardised mean differences (SMD) between intervention and comparison groups. Negative values for SMDs indicated outcomes in favour of the experimental group.

Results

Search yield

The search identified 9288 potentially relevant articles and 24 other articles were identified through other sources. Following screening of title and abstract, 47 articles were retrieved in full text. Twelve trials (16

articles) met the inclusion criteria for this review [12,18,45-47,49-60]. Most of them examined a range of physical outcome measures, however only data on patterns of muscle activity, lumbo-pelvic kinematics or posture patterns (as well as pain and activity scores) were extracted. A flow diagram of the study selection process is shown in Figure 1. The trials retrieved in full text and subsequently excluded are listed in Additional file 1, Appendix 2, together with reasons for their exclusion. Details of included studies are detailed in Additional file 1, Appendix 1. The wide variety of interventions and physical measures in the included trials prevented pooling in a meta-analysis.

Quality assessment

The method quality of the included trials is shown in Table 1. No trial included blinding of therapists or participants. This is not surprising, given how difficult this is to achieve in exercise or movement intervention trials. On the 0–10 quality scale, the mean score of included trials was 5.6 (range 3 to 8).

Types of trials found

Movement patterns measured by the included trials were classified into three arbitrary groups that measured: (i) specific trunk muscle activity patterns, (ii) 'flexion relaxation response' changes and (iii) various aspects of lumbo-pelvic kinematics and postural patterns. To focus the reporting, the analysis of results and the discussion were anchored to these three groups. Ten trials recruited people with chronic pain (> 3 months), one recruited

people with both acute and chronic pain, and one recruited people with pain for less than three weeks (see Table 2 and Additional file 1).

Trials measuring muscle activity patterns - intervention effects

Six of the 12 trials examined effects of interventions on specific muscle activity. Five trials compared motor control exercise, as described by Richardson et al. [26], with general exercise [12,47,49,56,57] and one trial compared Swiss ball exercise to general exercise [55]. Nine different outcome measures of muscle activity patterns were measured across the six trials and included TA thickness, TA movement, Lumbar Multifidus (LM) thickness, onset of contraction of the deep abdominal wall muscles and ratios of muscle activity.

Five trials (Table 3) included outcomes related to TA activity with one trial showing a statistically significant difference between experimental and comparison groups for changes to TA thickness [61] and another trial reporting a significant difference in the ratio of TA to Rectus Abdominus (RA) activity during double leg raise. [56]. No differences between groups were seen for TA movement [47] or deep abdominal wall muscle feed-forward timing [55,60]. Ferreira et al. [61] (Quality Assessment (QA) score 6/10) found significant (ANCOVA-adjusted) differences between groups in TA thickness ratio (contraction versus resting thickness) favouring motor control exercise (MCE) compared with either spinal manipulative therapy (SMT) or general exercise (GE). Effects adjusted for baseline differences were: MCE vs GE 12% greater

Figure 1 Flow diagram of study selection.

The figure contains the following boxes:

- 9288 records identified through database searching
- 24 additional records identified through other sources
- 6558 records after duplicates removed
- 6558 records screened by title and abstract
- 6511 records excluded
- 47 full text articles retrieved and assessed for eligibility
- 35 articles excluded
  Reasons for exclusion:
  - No data for health outcome = 6
  - No data for muscle activation, movement pattern or posture = 7
  - Non-painful control group = 5
  - Not an RCT = 4
  - Not available (unpublished PhD) = 1
  - Surgical intervention = 1
  - Groups not similar at baseline = 2
  - Whole body movement – no assessment of movement patterns = 9
- 12 studies included in review

Table 1 Quality assessment of included studies

PEDro criteria*	Akbari 2008	Da Fonesca 2009	Ferreira 2010	Haugstad 2006	Hides 1996&2001	Lalanne 2009	Magnussen 2008	Mannion 1999&2001	Marshall 2008	O'Sullivan 1997&1998	Ritaven 2007	Vasseljen 2010, 2012 & Unsgaard-Tonsel 2010
1. Eligibility criteria were specified	✓	✓	X	✓	✓	X	✓	✓	✓	✓	✓	✓
2. Random allocation of subjects	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3. Allocation was concealed	X	X	X	X	✓	X	X	X	X	✓	✓	✓
4. Groups similar at baseline	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
5. There was blinding of all subjects	X	X	X	X	X	X	X	X	X	X	X	X
6. Blinding of therapists	X	X	X	✓	X	X	X	X	X	X	X	X
7. Blinding of assessors	✓	X	✓	✓	✓	X	X	X	X	✓	✓	✓
8. >1 key outcome was obtained for more than 85% of subjects initially allocated to groups	X	✓	✓	X	✓	X	X	✓	✓	✓	✓	✓
9. All subjects . . . received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analysed by 'intention to treat'	X	✓	X	X	X	X	X	X	X	X	X	✓
10. The results of between-group statistical comparisons are reported for at least one key outcome	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
11. The study provides both point measures and measures of variability for at least one key outcome	X	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓
Total score	4	5	6	6	7	4	3	5	5	7	7	8
Assessor	PEDro	RL &PK	PEDro	PEDro	PEDro	PEDro	PEDro	PEDro	PEDro	PEDro	PEDro	RL &PK

* Item one is not included as part of the 10 point PEDro scoring.

Table 2 Summary of main categories of movement pattern investigated in the included studies

Type of pattern		Author	TA thickness	TA slide	TA + IO timing	LM thickness	Ratio muscle activitiy	FRR	Movement	Posture	Method of measurement	Characteristics of movement pattern measured	Pain	Activity limitation
			Components of movement pattern assessed								**Measurement details**		**Health outcomes**	
Muscle activation patterns	Specific muscle activity	**Akbari 2008** *Motor control vs general exercise*	✓			✓					Ultrasound	Muscle size - thickness at rest (mm)	✓	
		Hides 1996 & 2001 *Motor control exercise vs medical treatment*				✓					Ultrasound	Muscle size – cross sectional area (mm²)	✓	
		Ferreira 2010 *motor control exercise vs general ex vs spinal manipulative therapy*	✓								Ultrasound	Muscle thickness -% change from resting thickness	✓	✓
		Marshall 2008 *Swiss ball vs general exercise*		✓							Surface EMG	Feed forward activation	✓	✓
		O'Sullivan 1997 *Motor control vs GP management*					✓				Surface EMG	Internal Oblique and Rectus Abdominus electrical acitivity & ratio	✓	✓
		Vasseljen 2010, 2012 & Unsgaard-Tonsel 2010 *Motor control (low load) vs motor control (high load) vs general exercise*		✓			✓				Ultrasound	Size of muscle on contraction vs size of muscle at rest (ratio), Lateral slide (mm)	✓	✓
	Flexion relaxation response	**Lalanne 2009** *Manipulation vs manual therapy*						✓	✓		Surface EMG and Optoelectronic recording	Angle and intensity of onset and cessation of electrical activity	✓	✓
		Mannion 1999 & 2001 *Physiotherapy vs aerobics vs devices*						✓			Surface EMG	Intensity, onset and cessation of electrical activity	✓	✓
		Marshall 2008 *Swiss ball vs general exercise*						✓			Surface EMG	Intensity, onset and cessation of electrical activity	✓	✓
		Ritvanen 2007 *Traditional bone setting vs physiotherapy*						✓			Surface EMG	Intensity, onset and cessation of electrical activity	✓	✓
Movement patterns		**Da Fonesca 2009** *Pilates vs no Pilates control*							✓		Force plate and treadmill	Gait related forces and rates	✓	
		Magnusson 2008 *Postural biofeedback vs standardized rehab*							✓		Triaxial computerised goniometer	Circumduction area and velocity	✓	✓
Postural patterns		**Haugstad 2006 & 2008** *Mensendieck therapy vs standard gynaelogical treatment*								✓	Visual observation	Posture, upper and lower limb movement, gait, sitting posture and respiration	✓	✓

Table 3 Summary of results for studies that investigated intervention effects on muscle activity patterns (specific muscle activity)

Study and intervention type (experimental vs comparison)	No. of Subjects	TA thickness	TA slide*	TA & IO feedfoward timing	Multifidus (LM) thickness	Ratio of specific muscle activitiy	Baseline differences between groups?	SMD and 95%CIs *(negative values favour experimental/ motor control group)*	Pain	Activity	SMD and 95%CIs *(negative values favour experimental group)*
				Muscle activity patterns (specific muscle activity) — Movement pattern characteristics assessed. Was there a statistically significant difference (p < 0.05) in physical parameters *between* groups at the end of the intervention period? *(blank cell = not measured)*							
Akbari 2008 *Motor control exercise vs general exercise*	49	No			No		No (TA & LM) Pain: Yes[‡] Activity: Yes[‡]	Multifidus thickness −0.21 (−0.74 to 0.33) TA thickness −0.30 (−0.86 to 0.26)	Yes[‡]	Yes[‡]	Pain −1.06 (−1.66 to −0.46) Activity −0.70 (−1.27 to −0.12)
Hides 1996 *Motor control exercise vs control*	39			Yes[†,‖]			Insufficient data	Insufficient data	No[†]	No[†]	Insufficient data
Ferreira 2010 *Motor control exercise(MCE) vs general ex (GE) vs spinal manipulative therapy (SMT)*	34					Yes[††]	No	TA thickness ratio (contraction vs rest) MCE vs GE −0.29 (−0.44 to 0.57)[††] MCE vs SMT −0.70 (−0.42 to 0.12)[††]	No	No	Pain −0.32 (−0.44 to 0.54) MCE vs GE −0.51 (−0.42 to 0.30)MCE vs SMT Activity −0.25 (−1.11 to 0.61)MCE vs GE −0.63 (−0.42 to 0.19)MCE vs SMT
Marshall 2008 *Swiss ball vs general exercise*	50			No			No	Right feedforward activation of TA + IO −0.77 (−1.59 to 0.04) Left feedforward activation of TA + IO −0.46 (−1.25 to 0.34)	No	Yes	Activity −0.77 (−1.34 to −0.19)
O'Sullivan 1997 *Motor control exercise vs general exercise*	44					Yes	No	Ratio of TA + IO to RA −0.84 (−1.47 to −0.21)	Yes	No**	Pain −1.29 (−1.96 to −0.62) Activity −0.56 (−1.18 to 0.06)

Table 3 Summary of results for studies that investigated intervention effects on muscle activity patterns (specific muscle activity) *(Continued)*

Vasseljen 2010, 2012 & Unsgaard-Tonsel 2010 *Motor control (ultrasound guided exercise (US)) vs motor control (high load, sling exercise (SE)) vs general exercise (GE)*	109	No	No	No	No[§]	TA slide* 0.47 (−0.18 to 0.75) TA thickness ratio (contraction vs rest)[#]: TA 0.16 (−0.53 to 0.85) US vs GE IO 0.13 (−0.55 to 0.80) US vs GE EO 0.23 (−0.48 to 0.95) US vs GE TA feedforward timing:[§§] Minimal or no effect size for most comparisons No significant feedforward differences of clinical relevance	No	No	Pain −0.46 (−1.09 to 0.18) US vs GE −0.28 (−0.90 to 0.35) US vs SE Activity −0.54 (−1.16 to 0.10) US vs GE-0.34 -0.98 to 0.30-0.01) US vs SE

TA = Transversus Abdominus, LM = Lumbar Multifidus, EO = External Oblique, IO = Internal Oblique.

* TA slide = amount of distance (mm) lateral translation of musculotendinous junction present on contraction vs relaxation.

[†] As reported by the authors, but insufficient data for verification.

[‡] Our calculations show a statistically significant difference between groups for pain *and* activity, however the groups showed a significant difference at baseline which diminishes the strength of any conclusion about relative effectiveness of the intervention.

[§] No difference between groups at baseline was noted with the following exceptions: Left versus right differences were noted for the ultrasound guided group for IO ratio and TA lateral slide which created a statistically significant decrease in slide distance (reduced activation) and IO ratio post intervention for the left side only.

[‖] A statistically significant increase in favour of the experimental group for% size of Multifidus was reported by authors but insufficient data for verification.

Pain data obtained from Marshall 2008b, p331-332.

[#] Data for US versus SE groups similar.

** Our calculations of p value differ from those reported in the study, where we calculate p = 0.076 for post intervention activity levels (difference between groups post intervention) whereas the study reports p < 0.0001. However the six-month post intervention scores do reach significance (SMD = −0.73, 95%CI −1.35 to −0.11, p = 0.021).

[††] Authors present ANOVA data ($F_{2,31}$ = 4.09; p = 0.026) in favour of MCE vs GE (p = 0.043) and vs SMT (p = 0.053).

[§§] Side to side differences (nondominant versus dominant side) produced significant, small between-group differences favouring the SE group for the dominant side only (SEvs MCE and SEvs GE) after adjusting for baseline difference.

improvement (p = 0.043); MCE vs SMT 11.4% (p = 0.053). Unadjusted post-intervention differences between groups were not significant; SMDs: MCE vs SMT −0.70 (−0.42 to 0.12); MCE vs GE −0.29 (−0.44 to 0.57). O'Sullivan et al. [57] (QA 7/10) found a significant increase in the ratio of deep (TA and Internal Oblique) to superficial abdominal wall muscle (Rectus Abdominus) EMG activity favouring the motor control group over general exercise (SMD = -0.84, 95%CI −1.47 to −0.21, p = 0.01). Hides et al. [12] (QA 7/10) reported a significant increase in Multifidus size for the motor control group compared with a medical management group but did not provide data suitable for the calculation of effect sizes. Where significant differences between groups were found, effect sizes favouring specific muscle activity (see Table 3) were small to moderate (-0.20 to −0.47), with the exception of effects observed by O'Sullivan et al.

Trials measuring muscle activity patterns - relationship between changes in muscle activity and changes in pain or activity levels

Three trials found statistically significant differences between intervention and comparison groups for pain or activity limitation. Marshall et al. [55] (QA 5/10) found no effects for measures of muscle activation but a large effect for activity limitation (but not pain) in favour of the Swiss ball group (SMD = −0.77, 95%CI −1.34 to −0.19, p = 0.06). Akbari et al. [49] (QA 4/10) compared motor control exercise to general exercise and found no significant difference between groups for TA or LM thickness but reported a positive effect for pain (SMD = −1.06, 95%CI −1.66 to -0.46, p = 0.00) and activity limitation (SMD = −0.71, 95%CI −1.28 to −0.12, p = 0.02) favouring the motor control exercise group. The treatment and comparison groups in the Akbari et al. study were significantly different at baseline (the motor control exercise group had less pain and activity limitation at baseline), confounding interpretation of intervention effects on pain and activity levels. Hides et al. [12] reported a significant difference for LM size for the motor control group when compared with the control group but no differences for pain or activity limitation. O'Sullivan et al. [56,57] reported a difference between groups favouring motor control exercise for a movement pattern characteristic (ratio of deep to superficial abdominal muscle activity) and also for pain (SMD = −1.29, 95%CI −1.96 to-0.62, p = 0.00).

Trials measuring the flexion relaxation response - intervention effects

Four trials examined the muscle activation pattern known as the 'flexion relaxation response' (FRR) [51,53,55,58]. This refers to the electrical silence in lumbar extensors during full flexion typical of people without LBP; people with chronic LBP performing the same movement frequently exhibit continued electrical activity [62,63]. The FRR is a ratio where the numerator is electrical activity, measured by surface electromyography (EMG) of lumbar extensors while moving from standing to full flexion and back to standing and the denominator is EMG activity in the fully flexed position [64]. The ratio is largest in those without LBP where a normal finding would be minimal EMG activity in full flexion.

Lalanne et al. [51] (QA 4/10) compared FRR measured during a single session for people with chronic LBP who received manipulation compared with sham manipulation. They reported a significant improvement favouring the manipulation group (SMD = −1.40, 95%CI −2.24 to −0.56, p = 0.00). Marshall et al. [55] showed a significant difference in FRR favouring Swiss ball exercise over general exercise (SMD = −1.60 95%CI −2.25 to −0.94, p = 0.00). Mannion et al. [55] (QA 5/10) compared three interventions: (i) a 12-week physiotherapy group (advice, sub-maximal exercise, general strengthening, electrotherapy, heat or cold therapy, but not manual therapy), (ii) a strength training group (using devices), and (iii) an aerobics/stretching group. They found no post-intervention differences for FRR. Ritvanen et al. [60] (QA 7/10) evaluated the effects of traditional bone setting (a whole body manual therapy approach) compared with physiotherapy (massage, exercise and stretching) and found no significant post-intervention differences for FRR.

Trials measuring the FRR - the relationship between changes to muscle activity patterns and changes to pain or activity level

No trials reporting effects on FRR found differences between groups for pain (Table 4). Marshall et al. [55] reported an improvement in FRR (SMD = −0.77, 95%CI −1.34 to −0.19, p = 0.01) and improvement in activity levels both favouring Swiss ball exercise over general exercise.

Trials measuring lumbo-pelvic kinematics and postural patterns – intervention effects

Three trials examined intervention effects on lumbo-pelvic kinematic and/or postural patterns. Measurement methods included computerised triaxial inertial goniometry [52], treadmill with a force platform [65] and visual estimation from video image recording . Haugstad et al. [51] (QA 6/10) compared Mensendieck therapy (described as a somato-cognitive movement-based therapy) with medical management for women with chronic non-specific pelvic pain. They reported significant improvement in favour of the experimental group on various physical movement and postural parameters (sitting

Table 4 Summary of results for studies that investigated intervention effects on the Flexion relaxation response (FRR)

	Muscle activity patterns of FRR (electrical patterns of activity in extensor muscles during flexion and return from flexion) (Standardised mean difference and 95% confidence intervals, negative values favour experimental group)						
Study and intervention type	Study details		Movement pattern Was there a statistically significant difference (p > 0.05) in physical parameters *between* groups?				Health outcomes Was there a statistically significant difference (p < 0.05) in health outcomes between groups? groups?	
	No. of subjects	Baseline differences between groups?	FRR* Upper lumbar (T12-L3/4)	FRR* Lower lumbar (L4-S1)	Angle of onset and cessation for FRR	Extension vs flexion EMG ratio	Pain	Activity
Lalanne 2009‡ *Manipulation vs sham*	27	No	**Yes** ↑ -1.40 (−2.24, -0.56)	**No**	**No**	Not measured	**No**	Not measured
Mannion 1999 & 2001 *Physiotherapy vs aerobics Physiotherapy vs device strength training*	99	No	**No** † *Insufficient data*	**No** † *Insufficient data*	Not measured	Not measured	**No**	**No**
Marshall 2008 *Swiss ball vs general exercise*	50	No	**No**	**Yes** ↑ FRR in favour of intervention group −1.60 (−2.25, -0.94)	Not measured	Not measured	**No**	**Yes** Activity −0.77 (−1.34 to −0.19)
Ritvanen 2007 *Traditional bone setting vs physiotherapy*	61	(Intervention group had right vs left differences pre and post treatment)	**No**	**No** (both groups showed ↓ FRR post intervention	Not measured	**No** Trend towards increase for both groups	**No**	**No**

* *FRR = Flexion relaxation ratio (the amount of electrical activity in lumbar extensor muscles during flexion compared with end of flexion range of movement).*
† *As reported by authors. Insufficient data for analysis.*
‡ *Single session intervention with pre and post analysis within session.*

posture and respiration post-intervention, gait and movement at 12 months) with SMDs ranging from –1.64 to –0.89 (p = 0.00 to 0.004).

Magnusson et al. [52] (QA 3/10) compared postural biofeedback with a 'standard rehabilitation program' in people with chronic non-specific LBP and reported a significant increase in lumbo-pelvic circumduction area but did not provide the data required to estimate effect sizes. Da Fonesca et al. [45] (QA 5/10) compared Pilates exercise with a no treatment group in a small number (n = 17) of people with chronic non-specific LBP, and found no difference between groups for gait-related parameters.

Trials measuring lumbo-pelvic kinematics and postural patterns – relationship between changes in kinematic and postural patterns, and pain or activity levels

Haugstad et al. [50,66] reported large effects favouring Mensendieck therapy over medical management for a number of movement parameters (see Table 5) and pain (SMD = –1.71, 95%CI -2.46 to –0.97, p = 0.00). Magnusson et al. [52] reported an effect favouring postural biofeedback over a 'standard rehabilitation program' for movement (Table 5), pain (SMD = -3.60, 95%CI –4.5 to -2.6, p = 0.00) and activity limitation (SMD = –0.97, 95% CI -0.43 to –0.12, p = 0.00). DaFonesca et a [45] found no post-intervention difference between groups for physical parameters or pain.

Discussion

Despite the popularity of concepts such as core stabilisation, movement normalisation and postural correction, we found only 12 trials that measured both physical change in the targeted patterns of muscle activation, lumbo-pelvic kinematics or postural patterns, and pain or activity limitation outcomes. The small number of studies available for review highlights the limited knowledge base about the ability of interventions to change movement patterns and the clinical relevance of these changes to patient-centred outcomes.

Do interventions consistently change muscle activity patterns?

Muscle activation patterns were included in this review as they represent a specific type of movement pattern and are reportedly linked to therapeutic change with appropriate interventions Effect sizes for muscle activity pattern changes were inconsistent, mostly non-significant and generally small to moderate in size. Inconsistency may be explained by a number of factors including measurement differences. For example, Ferreira et al. [61] demonstrated significant between group differences in post intervention TA thickness favouring motor control exercise over both general exercise and

spinal manipulative therapy while Vasseljen et al. [47,60], in a high quality study (QA 8/10) found no difference between motor control, sling or general exercise groups. The difference in results between these two trials may have occurred due to differences in trial method. Ferreira et al. measured right sided, unilateral TA activity following isometric knee flexion/extension while Vasseljen et al. measured bilaterally during an abdominal muscle drawing in manoeuvre. Recent evidence suggests that left and right TA can activate differentially depending on perturbation of the trunk [67]. Unilateral measurement may be insufficient to draw conclusions about TA activity and its role in movement control.

Trials that evaluated the effects of various interventions on patterns of FRR had mixed outcomes, with two trials showing significant improvements in the FRR favouring the intervention groups [51,55] and two trials showing no difference [54,58]. Methodological differences between trials may also account for these variations in results. Marshall et al. [55] demonstrated a positive change to the FRR for a group of people with chronic LBP who performed high load, Swiss ball exercise (compared with general exercise) over a three-month period, while Lalanne et al. [53] used a within-session design comparing manipulative treatment with sham treatment, that demonstrated an immediate positive change to the FRR. The very different designs and interventions confound interpretation and comparison of results. Measurement and classification differences in the calculation of the FRR further constrain comparison of these four studies. Mannion et al. [53,68] used visual assessment to grade post-intervention changes to the FRR as 'improved, same, or worse' while the other three trials [51,55,58] computed a ratio of electrical activity in the movement period to electrical activity in the fully flexed period but used different formulae to compute this ratio. It is possible that people with LBP may have significant variation of flexion relaxation responses. It is also plausible that not all interventions will equally affect the FRR. Dankaerts et al. [69,70] demonstrated that different patterns of muscle activation and FRR are seen in people with chronic LBP during sitting. When comparing a group of unimpaired people with people with chronic LBP, no differences were identified until people with LBP were sub-classified into groups dependent on whether flexion or extension activity provoked pain. The group classified as having pain provoked by extension showed higher lumbar extensor muscle contraction activity, while the group with pain provoked by flexion showed lower levels of muscle activity in sitting when compared with the no-pain control group. If such patterns of muscle activation, posture and movement do exist and are clinically meaningful, this could affect the results of clinical

Table 5 Summary of results for studies that investigated intervention effects on lumbo-pelvic kinematic and postural patterns

Study and intervention type	No of subjects	Lumbo-pelvic kinematic and posture patterns (Standardised mean difference and 95% confidence intervals, values favour experimental group)							
		Movement pattern Was there a statistically significant difference ($p > 0.05$) in physical parameters *between* groups?						Health outcomes Was there a statistically significant difference ($p > 0.05$) in health outcomes between groups?	
		Baseline differences between groups?	Movement control	Gait	Standing posture	Respiration	Sitting posture	Pain	Activity
Da Fonesca 2009 *(Pilates vs No Rx group)*	17	No	Not measured	No*	Not measured	Not measured	Not measured	No −0.61, (−1.59-0.37)	Not measured
Haugstad 2006 *(Mensendieck somatocognitive therapy vs gynaecological management)*	40	No	No −0.15 (−1.29,0.98)	No −0.47 (−1.12,0.17),	No −0.20 (−0.84,0.44)	Yes −0.99 (−1.67, -0.31)	Yes −0.69 (−1.35, -0.03)	Yes[§] −1.58 (−2.31,-0.85)	Yes[†]
Haugstad 2008 *(Mensendieck somatocognitive therapy vs gynaecological management) 12-month post intervention from Haugstad 2006*	38	No	Yes −1.07 (−1.75,-0.39)	Yes − 0.89 (−1.56,-0.23)	No −0.56 (−1.20,0.09)	Yes −1.64 (−2.38,-0.91)	Yes −0.99 (−1.66,-0.31)	Yes −1.71 (−2.46,-0.97)	Yes[†]
Magnusson 2008 *(Postural biofeedback vs standardised rehabilitation)*	47	No[‖] Insufficient data	Yes[‡] Insufficient data	Not measured	Not measured	Not measured	Not measured	Yes −3.45 (−4.8 to −2.1)	Yes −0.97 (−0.43 to −0.12)

* No difference in gait-related parameters (vertical ground reaction forces at heel strike, mid stance, toes and rate of weight acceptance) between intervention and comparison groups except for a 3% increase in mid stance for the left leg only in the Pilates group.

[†] Measured as part of Mensendieck score, based on averaged scores for standing posture, movement, gait, sitting posture and respiration, $p < 0.000$.

[‡] As reported by author. Insufficient data provided for analysis.

[§] Small baseline difference between groups $p < 0.05$.

[‖] No baseline difference for pain or activity levels but insufficient data for physical parameters.

[¶] Calculated on the lowest number of subjects.

trials. In theory, a trial with a greater proportion of participants with a particular pattern of chronic LBP may have different outcomes compared to trials of participants with different patterns of muscle activation.

The relationship of change to muscle activation patterns and changes to pain and activity limitation

The available evidence suggests little consistent relationship exists between changes to pain and/or activity level and the direction of changes to muscle activity. Changes to muscle activation patterns have been reported without corresponding change to pain or activity, while the opposite has also been reported. One could reasonably expect that if a muscle activation deficit was consistently contributing to pain or activity restriction in the broad population of people with LBP, improvements in pain and activity level would occur in conjunction with improvement in that muscle deficit. Five trials investigated changes in TA activity, with only one reporting an association between changes in TA function and associated changes in pain or activity limitation. Two trials, one involving people with acute LBP [12] and the other with chronic LBP [49], investigated Lumbar Multifidus (LM) function following motor control exercise interventions. The Hides trial [12] of people with acute LBP suggests that improvement in LM size is not directly associated with improvement in pain or activity levels. The Akbari trial [49] of people with chronic LBP that compared motor control with general exercise, found no significant post-intervention differences between groups for TA or LM size, but did find a significant improvement in pain and activity favouring the motor control group. Both the Hides and Akbari trials used ultrasound measurement of LM, which has been shown to be sensitive to changes in lumbar and abdominal muscle [71]. These findings provide preliminary evidence that changes in pain and/or activity can occur without observable change to TA or LM size and *vice versa*. O'Sullivan et al. [56,57] found a significant difference in a pattern of muscle activation (ratio of deep to superficial abdominal muscle activity), and also in both pain and activity levels, favouring motor control exercise. However the O'Sullivan et al. study differs from other studies by investigating a subgroup of chronic LBP subjects (spondylolisthesis with specific symptom pattern), while the other studies in this review included people with non-specific chronic LBP. It also differs from the other included studies with respect to the large differences observed between intervention (motor control) and control (medical management) outcomes. The improvement seen in muscle activation patterns and the related improvements in pain and activity warrant replication in another study if clinicians are to have confidence that similar outcomes would occur in the general LBP population. Recent reviews of motor control exercise for general chronic LBP populations have not concluded similar effects for pain or activity [38,39,72] and no other trials could be found that measured the ratio of deep to superficial muscle activity.

No picture emerged of a relationship between change in FRR and change in pain and activity. Marshall et al. [55] found statistically significant improvement in activity limitation favouring the experimental group. However neither of the two trials [51,55] that found improvement in FRR favouring the intervention group, were associated with any difference between groups for pain outcomes. Geisser et al. [63] in a systematic review found 11 studies comparing EMG of dynamic lumbar extensor muscle activity of people with chronic LBP with normal subjects, four of which specifically examined differences in the FRR. Based on meta-analytic pooling data from four comparable studies, they concluded that the evidence supports the FRR being a useful, measurable movement characteristic that differentiates people with LBP from people without LBP (SMD = −1.71, 95%CI −2.25 to −1.36). A recent pilot study of chronic LBP[73] showed that EMG biofeedback plus functional restoration was better than functional restoration alone in improving FRR. However the relationship between change to the FRR and changes to pain or activity limitation remains poorly explored. Increased standardisation of FRR measurement combined with a better understanding of typical variability in FRR in people with chronic LBP will be required before the implications of measuring and modifying the FRR become clear.

Lumbo-pelvic kinematic and postural patterns

Three trials examined lumbo-pelvic kinematic and postural patterns, with only one focused on posture. The concept of changing movement or postural patterns is fundamental to many popular movement-based interventions but is rarely measured in trials of the effects of interventions. Magnusson [52] reported changes to lumbo-pelvic circumduction area favouring the postural biofeedback intervention group with associated improvements in pain and activity also favouring the intervention group. The effect sizes favouring the postural biofeedback intervention group were unusually large, and a replication study is therefore warranted. Haugstad et al. [50,66] found large and statistically significant effects in respiration and posture in favour of the intervention group using Mensendieck therapy for women with non-specific pelvic pain, as well as significant improvements in pain and activity limitation. At 12-month follow-up, the intervention group showed further improvement in movement control, gait, respiration and posture, and reduction in pain relative to the control group. In contrast, a trial by Soukup and Glomsrod [74] comparing Mensendieck therapy to a no treatment

control group for people with chronic LBP found that although 12-month recurrence rates were significantly lower for the intervention group, there were no post-intervention differences between groups for pain or activity limitation. Despite a common assumption that posture is related to LBP, studies of interventions that include measurement of changes to posture are scarce, and a relationship between postural modification and improvements to pain or activity limitation has not been established.

Measurement methods and reliability

It was beyond the scope of this review to assess the reliability of instruments used to measure movement patterns. However clinicians and researchers need to remain attentive to how movement patterns can be reliably measured and the minimal amount of change required for clinical relevance.

Study limitations

The strengths of this systematic review are the comprehensive search strategy of a diverse selection of electronic databases, screening and data extraction by two independent reviewers. Furthermore, included studies needed to quantify a change in the targeted movement pattern so as to link that physical outcome with subsequent changes in patient-centred outcomes. The review also has limitations. Due to an absence of translation resources, only articles published in English were included and this may introduce a language, cultural and/or publication bias. The classification categories of movement patterns were necessarily arbitrary but were designed to include the most common characteristics observed in practice.

Conclusions

This review establishes that despite the popularity of movement-related interventions, there are few clinical trials that quantify the effect of interventions for people with LBP on the outcomes of change in muscle activity, lumbo-pelvic kinematic or postural patterns. The available evidence on muscle activity pattern changes following therapeutic interventions indicates little difference in outcomes between a general exercise program and specific interventions that aim to change the activity of trunk muscles such as Transversus Abdominus and Lumbar Multifidus. That same evidence suggests that improved pain or activity limitation are consistently unrelated to changes in the activity of specific muscles. There is conflicting evidence of the effectiveness of interventions that measure changes to the flexion relaxation response, possibly due to differing trial designs and participant differences. The relationship between intervention-related change to the flexion relaxation response and changes to pain or activity limitation are also unclear. Trials of interventions that aim to change lumbo-pelvic kinematic and postural patterns are few in number, and too varied in design, to draw firm conclusions.

Overall, our ability to change movement patterns with specific interventions is not well supported by the research currently available. There is little evidence that pain and activity limitation change in concert with desirable changes to movement patterns. More research with better designs is required to advance our understanding of movement-modification through exercise.

Addtional file

> **Additional file 1: Appendix 1. Details of included studies; Appendix 2. List of excluded studies and brief reason for exclusion.**

Abbreviations
Low back pain: LBP; Transversus abdominus: TA; Lumbar multifidus: LM; Internal oblique: IO; External oblique: EO; Standardised mean difference: SMD; Flexion relaxation response: FRR.

Author details
[1]Department of Physiotherapy, Monash University, PO Box 527, Frankston, Victoria 3199, Australia. [2]Research Department, Spine Centre of Southern Denmark, Lillibaelt Hospital, Institute of Regional Health Services Research, University of Southern Denmark, Middelfart, Denmark. [3]Postal Address: 7 Kerry Rd, Warranwood, Melbourne, Victoria 3134, Australia.

References
1. Weiner BK: **The biopsychosocial model and spine care.** *Spine* 2008, **33**(2):219–223.
2. Waddell G: **Low Back Pain: A Twentieth Century Health Care Enigma.** *Spine* 1996, **21**(24):2820–2825.
3. Kent P, Keating JL: **Classification in non-specific low back pain - what methods do primary care clinicians currently use?** *Spine* 2005, **30**:1434–1440.
4. Koes B, van Tulder M, Thomas S: **Diagnosis and treatment of low back pain.** *Br Med J* 2006, **332**:1430–1434.
5. Battié MC, Videman T, Kaprio J, Gibbons LE, Gill K, Manninen H, Saarela J, Peltonen L: **The Twin Spine Study: Contributions to a changing view of disc degeneration.** *Spine J* 2009, **9**(1):47–59.

6. Smith A, O'Sullivan P, Straker L: Classification of sagittal thoraco-lumbo-pelvic alignment of the adolescent spine in standing and its relationship to low back pain. *Spine* 2008, 33(19):2101–2107.
7. Scannell J, McGill S: Lumbar posture-should it, and can it, be modified? A study of passive tissue stiffness and lumbar position during activities of daily living. *Phys Ther* 2003, 83(10):907–917.
8. Teyhen DS, Flynn TW, Childs JD, Abraham LD: Arthrokinematics in a subgroup of patients likely to benefit from a lumbar stabilization exercise program. *Phys Ther* 2007, 87(3):313–325.
9. Hodges P, van den Hoorn W, Dawson A, Cholewicki J: Changes in the mechanical properties of the trunk in low back pain may be associated with recurrence. *J Biomech* 2009, 42(1):61–66.
10. Hodges P, Richardson C: Inefficient muscular stabilization of the lumbar spine associated with low back pain: a motor control evaluation of transversus abdominus. *Spine* 1996, 21(22):2640–2650.
11. Lee J, Hoshino Y, Nakamura K, Ooi Y: Trunk muscle imbalance as a risk factor of the incidence of low back pain: a 5-year propsective [sic] study. *J Neuomusculoskeletal Syst* 1999, 7(3):97–101.
12. Hides JA, Richardson CA, Jull GA: Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain. *Spine* 1996, 21(23):2763–2769.
13. Van Daele U, Hagman F, Truijen S, Vorlat P, Van Gheluwe B, Vaes P: Decrease in postural sway and trunk stiffness during cognitive dual-task in nonspecific chronic low back pain patients, performance compared to healthy control subjects. *Spine* 2010, 35(5):583–589.
14. Descarreaux M, Blouin J-S, Teasdale N: Repositioning accuracy and movement parameters in low back pain subjects and healthy control subjects. *Eur Spine J* 2005, 14(2):185–191.
15. Silfies SP, Mehta R, Smith SS, Karduna AR: Differences in Feedforward Trunk Muscle Activity in Subgroups of Patients With Mechanical Low Back Pain. *Arch Phys Med Rehabil* 2009, 90(7):1159–1169.
16. Wallwork TL, Stanton WR, Freke M, Hides JA: The effect of chronic low back pain on size and contraction of the lumbar multifidus muscle. *Man Ther* 2009, 14(5):496–500.
17. Hides J, Gilmore C, Stanton W, Bohlscheid E: Multifidus size and symmetry among chronic LBP and healthy asymptomatic subjects. *Man Ther* 2008, 13(1):43–49.
18. Hides JA, Jull GA, Richardson CA: Long-term effects of specific stabilizing exercises for first-episode low back pain. *Spine* 2001, 26(11):E243–248.
19. Dunk NM, Callaghan JP: Lumbar spine movement patterns during prolonged sitting differentiate low back pain developers from matched asymptomatic controls. *Work* 2010, 35(1):3–14.
20. Williams MM, Hawley JA, McKenzie RA, van Wijmen PM: A comparison of the effects of two sitting postures on back and referred pain. *Spine* 1991, 16(10):1185–1191.
21. Gregory DE, Callaghan JP, Gregory DE, Callaghan JP: Prolonged standing as a precursor for the development of low back discomfort: an investigation of possible mechanisms. *Gait Posture* 2008, 28(1):86–92.
22. Esola MA, McClure PW, Fitzgerald GK, Siegler S: Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain. *Spine* 1996, 21(1):71–78.
23. McClure PW, Esola M, Schreier R, Siegler S: Kinematic analysis of lumbar and hip motion while rising from a forward, flexed position in patients with and without a history of low back pain. *Spine* 1997, 22(5):552–558.
24. Silfies SP, Bhattacharya A, Biely S, Smith SS, Giszter S: Trunk control during standing reach: A dynamical system analysis of movement strategies in patients with mechanical low back pain. *Gait Posture* 2009, 29(3):370–376.
25. Shum GL, Crosbie J, Lee RYW: Three-Dimensional Kinetics of the Lumbar Spine and Hips in Low Back Pain Patients During Sit-to-Stand and Stand-to-Sit. *Spine* 2007, 32(7):E211–E219.
26. Richardson C, Jull G, Hodges P, Hides J: *Therapeutic exercise for spinal segmental stabilization in low back pain: scientific basis and clinical approach.* Edinburgh: Churchill Livingstone; 1999.
27. Bryan M, Hawson S: The Benefits of Pilates Exercise in Orthopaedic Rehabilitation. *Tech Orthop* March 2003, 18(1):126–129.
28. McKenzie R, May S: *Lumbar Spine, Mechanical Diagnosis and Therapy.* 2nd edition. Waikanae, New Zealand: Spinal Publications Ltd; 2003.
29. Van Dillen LR, Sahrmann SA, Norton BJ, Caldwell CA, McDonnell MK, Bloom N: The effect of modifying patient-preferred spinal movement and alignment during symptom testing in patients with low back pain: a preliminary report. *Arch Phys Med Rehabil* 2003, 84(3):313–322.
30. Slade SC, Keating JL: Trunk-strengthening exercises for chronic low back pain: a systematic review. *J Manipulative Physiol Ther* 2006, 29(2):163–173.
31. Slade SC, Keating JL: Unloaded movement facilitation exercise compared to no exercise or alternative therapy on outcomes for people with nonspecific chronic low back pain: a systematic review. *J Manipulative Physiol Ther* 2007, 30(4):301–311.
32. van Middelkoop M, Rubinstein SM, Verhagen AP, Ostelo RW, Koes BW, van Tulder MW: Exercise therapy for chronic nonspecific low-back pain. *Best Pract Clin Rheumatol* 2010, 24(2):193–204.
33. Ernst E, Canter PH: The Alexander technique: a systematic review of controlled clinical trials. *Forsch Komplementarmed Klass Naturheilkd* 2003, 10(6):325–329.
34. Little P, Lewith G, Webley F, Evans M, Beattie A, Middleton K, Barnett J, Ballard K, Oxford F, Smith P, *et al*: Randomised controlled trial of Alexander technique lessons, exercise, and massage (ATEAM) for chronic and recurrent back pain.[see comment]. *BMJ* 2008, 337:a884.
35. Lim ECW, Poh RLC, Low AY, Wong WP: Effects of Pilates-Based Exercises on Pain and Disability in Individuals With Persistent Nonspecific Low Back Pain: A Systematic Review With Meta-analysis. *J Orthop Sports Phys Ther* 2011, 41(2):70–80.
36. Ferreira P, Ferreira M, Maher C, Herbert R, Refshauge K: Specific stabilisation exercise for spinal and pelvic pain: A systematic review. *J Physiother* 2006, 52:79–88.
37. Hauggaard A, Persson AL: Specific spinal stabilisation exercises in patients with low back pain – a systematic review. *Phys Ther Rev* 2007, 12(3):233–248.
38. Macedo LG, Maher CG, Latimer J, McAuley JH: Motor Control Exercise for Persistent, Nonspecific Low Back Pain: A Systematic Review. *Phys Ther* 2009, 89(1):9–25.
39. May S, Johnson R: Stabilisation exercises for low back pain: a systematic review. *Physiotherapy* 2008, 94(3):179–189.
40. Rackwitz B, DeBie R, Ewert T, Stucki G: Segmental stabilizing exercises and low back pain. What is the evidence? A systematic review of randomized controlled trials. *Clin Rehabil* 2006, 20:553–567.
41. Ferreira PH, Ferreira ML, Hodges PW: Changes in recruitment of the abdominal muscles in people with low back pain ultrasound measurement of muscle activity. *Spine* 2004, 29(2):2560–2566.
42. Verhagen AP, de Vet HCW, de Bie RA, Kessels AGH, Boers M, Bouter LM, Knipschild PG: The Delphi List: A Criteria List for Quality Assessment of Randomized Clinical Trials for Conducting Systematic Reviews Developed by Delphi Consensus. *J Clin Epidemiol* 1998, 51(12):1235–1241.
43. Maher CG, Sherrington C, Herbert RD, Moseley AM, Elkins A: Reliability of the PEDro scale for rating quality of randomized controlled trials. *Phys Ther* 2003, 83:713–721.
44. de Morton N: The PEDro scale is a valid measure of the methodological quality of clinical trials: a demographic study. *J Physiother* 2009, 55(2):192–133.
45. da Fonseca JL, Magini M, de Freitas TH: Laboratory gait analysis in patients with low back pain before and after a pilates intervention. *J Sport Rehabil* 2009, 18(2):269–282.
46. Unsgaard-Tondel M, Fladmark AM, Salveson O, Vasseljen O: Motor control exercises, sling exercises and general exercises for patients with CLBP: a RCT with 1 year follow-up. *Phys Ther* 2010, 90(10):1–14.
47. Vasseljen O, Fladmark AM: Abdominal muscle contraction thickness and function after specific and general exercises: A randomized controlled trial in chronic low back pain patients. *Man Ther* 2010, 15(5):482–489.
48. Review Manager (RevMan). In. 50th edition. Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration; 2008.
49. Akbari A, Khorashadizadeh S, Abdi G: The effect of motor control exercise versus general exercise on lumbar local stabilizing muscles thickness: randomized controlled trial of patients with chronic low back pain. *J Back Musculoskel Rehabil* 2008, 21(2):105–112.
50. Haugstad GK, Haugstad TS, Kirste UM, Leganger S, Wojniusz S, Klemmetsen I, Malt UF: Continuing improvement of chronic pelvic pain in women after short-term Mensendieck somatocognitive therapy: results of a 1-year follow-up study. *Am J Obstet Gynecol* 2008, 199(6):e611–e618.
51. Lalanne K, Lafond D, Descarreaux M: Modulation of the flexion-relaxation response by spinal manipulative therapy: a control group study. *J Manipulative Physiol Ther* 2009, 32(3):203–209.
52. Magnusson ML, Chow DH, Diamandopoulos Z, Pope MH: Motor control learning in chronic low back pain. *Spine* 2008, 33(16):E532–538.

53. Mannion AF, Muntener M, Taimela S, Dvorak J: **1999 Volvo Award Winner in Clinical Studies: a randomized clinical trial of three active therapies for chronic low back pain.** *Spine* 1999, **24**(23):2435–2448.
54. Mannion AF, Taimela S, Muntener M, Dvorak J: **Active therapy for chronic low back pain part 1. Effects on back muscle activation, fatigability, and strength.** *Spine* 2001, **26**(8):897–908.
55. Marshall P, Murphy B: **Muscle activation changes after exercise rehabilitation for chronic low back pain.** *Arch Phys Med Rehabil* 2008, **89**(7):1305–1313.
56. O'Sullivan P, Twomey L, Allison G: **Altered abdominal muscle recruitment in patients with chronic back pain following a specific exercise intervention.** *J Orthop Sports Phys Ther* 1998, **27**(2):114–124.
57. O'Sullivan P, Twomey LT, Allison GT: **Evaluation of specific stabilizing exercise in the treatment of chronic low back pain with radiologic diagnosis of spondylolysis or spondylolisthesis.** *Spine* 1997, **22**(24):2959–2967.
58. Ritvanen T, Zaproudina N, Nissen M, Leinonen V, HÄnninen O: **Dynamic Surface Electromyographic Responses in Chronic Low Back Pain Treated by Traditional Bone Setting and Conventional Physical Therapy.** *J Manipulative Physiol Ther* 2007, **30**(1):31–37.
59. Freeman MD, Woodham MA, Woodham AW: **The role of the lumbar multifidus in chronic low back pain: a review.** *Pm & R* 2010, **2**(2):142–146. quiz 141 p following 167.
60. Vasseljen O, Unsgaard-Tondel M, Westad C, Mork P: **Effect of Core Stability Exercises on Feedforward Activation of Deep Abdominal Muscles in Chronic Low Back Pain: A Randomized Controlled Trial.** *Spine* 2012.
61. Ferreira P, Ferreira M, Maher C, Refshauge K, Herbert R, Hodges P: **Changes in recruitment of transversus abdominis correlate with disability in people with chronic low back pain.** *Br J Sports Med* 2010, **44**:1166–1172.
62. Neblett R, Mayer TG, Gatchel RJ, Keeley J, Proctor T, Anagnostis C: **Quantifying the lumbar flexion-relaxation phenomenon: theory, normative data, and clinical applications.** *Spine* 2003, **28**(13):1435–1446.
63. Geisser ME, Ranavaya M, Haig AJ, Roth RS, Zucker R, Ambroz C, Caruso M: **A meta-analytic review of surface electromyography among persons with low back pain and normal, healthy controls.** *J Pain* 2005, **6**(11):711–726.
64. Watson P, Booker C, Main C, Chen A: **Surface electromyography in the identification of chronic low back pain patients: the development of the flexion relaxation ratio.** *Clin Biomech* 1997, **12**:165–171.
65. de Fonseca JL, Magini M, de Freitas TH: **Laboratory gait analysis in patients with low back pain before and after a Pilates intervention.** *J Sport Rehabil* 2009, **18**(2):269–282.
66. Haugstad GK, Haugstad TS, Kirste UM, Leganger S, Klemmetsen I, Malt UF: **Mensendieck somatocognitive therapy as treatment approach to chronic pelvic pain: results of a randomized controlled intervention study.** *Am J Obstet Gynecol* 2006, **194**(5):1303–1310.
67. Morris SL, Lay B, Allison GT: **Corset hypothesis rebutted — Transversus abdominis does not co-contract in unison prior to rapid arm movements.** *Clin Biomech* 2012, **27**:249–254.
68. Mannion AF, Junge A, Taimela S, Muntener M, Lorenzo K, Dvorak J: **Active therapy for chronic low back pain: part 3. Factors influencing self-rated disability and its change following therapy.** *Spine* 2001, **26**(8):920–929.
69. Dankaerts W, O'Sullivan P, Burnett A, Straker L, Dankaerts W, O'Sullivan P, Burnett A, Straker L: **Differences in sitting postures are associated with nonspecific chronic low back pain disorders when patients are subclassified.** *Spine* 2006, **31**(6):698–704.
70. Dankaerts W, O'Sullivan P, Burnett A, Straker L, Dankaerts W, O'Sullivan P, Burnett A, Straker L: **Altered patterns of superficial trunk muscle activation during sitting in nonspecific chronic low back pain patients: importance of subclassification.** *Spine* 2006, **31**(17):2017–2023.
71. Koppenhaver SL, Hebert JJ, Parent EC, Fritz JM: **Rehabilitative ultrasound imaging is a valid measure of trunk muscle size and activation during most isometric sub-maximal contractions: a systematic review.** *J Physiother* 2009, **55**(3):153–169.
72. Ferreira ML, Ferreira PH, Latimer J, Herbert RD, Hodges PW, Jennings MD, Maher CG, Refshauge KM: **Comparison of general exercise, motor control exercise and spinal manipulative therapy for chronic low back pain: A randomized trial.** *Pain* 2007, **131**(1–2):31–37.
73. Neblett R, Mayer TG, Brede E, Gatchel RJ: **Correcting abnormal flexion-relaxation in chronic lumbar pain: responsiveness to a new biofeedback training protocol.** *Clin J Pain* 2010, **26**(5):403–409.
74. Soukup MG, Glomsrod B, Lonn JH, Bo K, Larsen S: **The effect of a Mensendieck exercise program as secondary prophylaxis for recurrent low back pain. A randomized, controlled trial with 12-month follow-up.** *Spine* 1999, **24**(15):1585–1591. discussion 1592.

9.2.   Appendix B: Details and characteristics of included studies by Laird et al. (2012)

Study details	Inclusion and exclusion criteria	Intervention/Comparison treatments	Outcome measurements	Timing of outcome measures
Akbari 2008 *Source:* • Physiotherapy clinics *Type of condition:* • Chronic LBP[1] *Number of subjects:* • N=49 post intervention (58 at baseline)	*Inclusion Criteria* • 18-80 years old • Non-specific LBP +/- leg pain, • > 3 months duration *Exclusion Criteria* • Serious spinal pathology • Pregnancy • Neurological compromise • Previous surgery • p. 42 ASCM guidelines[3]	*Intervention group (n=25)* • Muscle activation exercise program (low load activation of stabilising muscles) • 16 sessions over 8 weeks (30 min per session) *Comparison group (n=24)* • General exercise program • 16 sessions over 8 weeks (30 min per session)	***Physical measures:*** • Muscle thickness (mm) of Transversus Abdominis (TA) and Lumbar Multifidus (LM) at rest ***Measurement method*** • Ultrasound ***Health outcomes***: • VAS[2] • Back performance scale (0-15 scale)	• Pre and post intervention (no details specified)
Da Fonesca 2009 *Source:* Waiting list for physiotherapy *Type of condition:* • Not stated *Number of subjects:* • N=17 (Rx group n=8, No Rx group n=9) + n=11 no pain controls, post intervention and at baseline	*Inclusion Criteria* • Age 18-59 years • Chronic LBP +/- leg pain > 6 months • Independent gait *Exclusion Criteria* • Neurological disease • Major visual deficit • True leg length discrepancy > 2 cm • Ankylosing spondylitis • Spine fusion surgery • Lower extremity surgery within 1 year	*Intervention group (N=8)* • 15 sessions of Pilates, 2 sessions per week, (over 8 weeks but not specifically stated) *Comparison group (n=9)* • No treatment	***Physical measures:*** • Parameters related to gait analysis of ground reaction forces (% body weight): - 1st peak force (force of heel strike) - 2nd peak force (force of toe off) - Middle support force (force mid stance) - Weight acceptance rate (left or right leg) - Push off rate ***Measurement method*** • Force plate/treadmill ***Health outcomes***: • VAS • Present pain intensity (0-5 point scale)	• Pre and post intervention (no details specified)

Ferreira 2010 *Source:* Public hospital physical therapy depts. *Type of condition:* • Chronic non-specific LBP *Number of subjects:* • N=34 (Muscle activation exercise n=11, general exercise n=10, spinal manipulative therapy n=13, post intervention and at baseline)	*Inclusion Criteria* • Age 18-80 years • Chronic LBP +/- leg pain > 3 months • >2 on 0-10 on pain scale • >3 on Roland Morris Disability Questionnaire *Exclusion Criteria* • Neurological deficit • Spinal surgery previous 12 months • Pregnancy • Serious or specific spine pathology • Poor English comprehension • Any contraindication to exercise	*Intervention group (N=11)* • Average of 8.7 sessions of muscle activation exercise (Multifidus, TA, control of neutral posture + reduction on excessive superficial trunk muscle activation *Comparison group – General exercise (n=10)* • Average of 11.2 sessions of a program described by Klaber et al(Klaber Moffett J et al., 2000) *Comparison group – spinal manipulative therapy (n=13)* Joint mobilisation at clinician's discretion (no high velocity thrusts)	***Physical measures:*** - TA % thickness on contraction compared with resting thickness ***Measurement method*** • Ultrasound ***Health outcomes***: • Global impression of recovery (11-point scale) • NRS • Roland Morris Disability Questionnaire (2- item)	• Pre and post intervention (baseline and 8 weeks)
Haugstad 2006 *Source:* • Gynaecological outpatient clinic *Type of condition:* • Chronic pelvic pain *Number of subjects:* • N=38 post intervention (40 at baseline)	*Inclusion Criteria* • Age 20-50 years • Chronic pelvic girdle pain > 1 year *Exclusion Criteria* • Neurological deficit or disease • Spinal canal stenosis • Lumbar disc herniation • Specific gynaecological disease • Psychological disease (bipolar, eating disorder, psychosis etc)	*Intervention group (n=19)* • Standard gynaecological treatment (STGT) and Mensendieck somatocognitive therapy (MSCT). • Rx Group received 10 x 60 min treatments sessions with the Mensendieck therapist over 90 days (in addition to the gynaecological interventions). *Comparison group (n=19)* • Standard gynaecological treatment (STGT) (x2 sessions with gynaecologist for medication and advice)	***Physical measures:*** • Mensendieck performance score (Haugstad, G et al., 2006a)(0-7 scale for each area, where 7 is best) ***Measurement method*** • Visual observation ***Health outcomes***: • Visual observation (standing posture, movement, gait, sitting posture, respiration) • VAS	• Mensendieck score at baseline, 6.5 and 13 weeks • VAS and pain diary at baseline and 13 weeks
Hides 1996 *Source:* • Emergency department, public hospital *Type of condition:* • Acute first episode unilateral, mechanical LBP *Number of subjects:* • N=39 post intervention (41 at baseline)	*Inclusion Criteria* • Age 18-45 years • Acute 1st episode unilateral LBP +/- leg referral, pain between T12 and gluteal fold, + restricted lumbar ROM *Exclusion Criteria* • Previous history of LBP or injury, previous lumbar surgery, spinal abnormalities indicated on radiographs, neuromuscular or joint disease, reflex and/or motor signs of nerve root compression or cauda equina compression, evidence of systemic disease, carcinoma or organ disease, pregnancy, sports or fitness training involving the low back muscles undertaken in the past 3 months.	*Intervention group (n=20)* • Medical Rx (advice, medication) and localised, specific exercise (using ultrasound guided feedback of Multifidus) in standing, neutral position with co-contraction of TA • 4 weeks of training *Comparison group (n=19)* • Medical Rx (advice, drug prescription - analgesia, NSAIDs, muscle relaxants)	***Physical measures:*** • Muscle CSA Multifidus • Lumbar range of movement (ROM) & Straight leg raise (SLR) using double or single inclinometer ***Measurement method*** • Ultrasound ***Health outcomes***: • Pain (McGill Pain Questionnaire) • VAS and pain diary • Roland Morris Disability Questionnaire (RMDQ) • ROM • Habitual activity questionnaire	• Assessed at baseline, 4 weeks and 10 weeks

Lalanne 2009
Source:
• Not stated
Type of condition:
• Chronic LBP
Number of subjects:
• N=27 post intervention and at baseline
	Inclusion Criteria
	• Chronic LBP > 6 months
	Exclusion Criteria
	• Spondylolisthesis, axial skeletal inflammation or osteoarthritis, collagenosis, osteoporosis, spinal surgery, neuromuscular disease, lower limb musculoskeletal injuries, malignant tumour, hypertension, infection or any other nonmechanical condition, radiculopathy, progressive neurological deficit, myelopathy, herniated lumbar disk, and severe pain (more than 7 on a 0-10 VAS scale).
		Intervention group (n=13)
		• 5 lumbar flexion-extension cycles (5 second flexion, 5 second hold, 5 second return)
		• Rotational manipulation
		Comparison group (n=14)
		• 5 Flexion-extension cycles 5 sec flexion, 5 sec hold, 5 sec return)
		• Rotational position only
			Physical measures:
			• Electrical activity of erector spinae
			  - Normalised RMS
			  - Mean Flexion relaxation ratio
			  - Angle of onset (L2, L5)
			  - Angle of cessation (L2, L5)
			Measurement method
			• Surface electromyography (sEMG)
			• Optoelectronic recording (Optotrak)
			Health outcomes:
			• Oswestry Disability Index (ODI)
			• VAS
			• Fear avoidance beliefs (FABQ)
				• Single intervention with pre and post analysis within session

Magnusson 2008 *Source:* • Referral to back rehabilitation centre *Type of condition:* • Chronic LBP > 6 months *Number of subjects:* • N=47 at baseline (post intervention numbers)	*Inclusion Criteria* • Chronic low back pain +/- leg pain • Aged 20 to 70 years • Male or female • Symptoms continuous for 6 months or more, or recurrent (not defined) • Fit for rehabilitation program *Exclusion Criteria* • Fracture, tumour, infection • Severe peripheral vascular disease • Symptomatic knee or hip arthritis • CNS disorders or peripheral neuropathology • Significant psychopathologic conditions	*Intervention group (n=19)* • Standardised rehabilitation (5x1 hour sessions – advice, exercise for strengthening, posture and mobility, teaches self-management strategies) AND • Postural biofeedback • 10 x 30 min sessions over 5 weeks *Comparison group (n=19)* • Standardised rehabilitation program (5 x 1-hour sessions – advice, exercise for strengthening, posture and mobility, teaches self-management strategies)	***Physical measures:*** • Lumbar ROM patterns, combined movement (circumduction) and velocity ***Measurement method*** • Back Tracker (triaxial electrical goniometer) ***Health outcomes***: • VAS • SF 36	• Baseline, 6 and 28 weeks

Mannion 1999 & 2001
Source:
• Community sourced via advertisement
Type of condition:
• Chronic LBP
Number of subjects:
• N=132 (See also Mannion 1999) post intervention (147 at baseline)
	Inclusion Criteria
	• < 65 years
	• Chronic LBP > 3 months +/- leg pain (non-radicular)
	• Ability to perform seated lifting 3-5kg from knee height to upright x15 in 30 sec
	Exclusion Criteria
	• Constant or persistent severe pain, nonmechanical LBP, pregnancy, previous spinal surgery, current nerve root entrap + neurologic deficit, spinal cord compression, tumours, severe structural deformity or instability or osteoporosis or cardiovascular or metabolic disease, recent fracture, inflammatory or infectious disease of the spine, other disorders preventing active rehabilitation, and lack of cooperation.
		Intervention group(s) (n=46)
		1. Physiotherapy (30 minutes, individual sessions),
		  - Instruction on ergonomics
		  - Submaximal exercise (isometric and theraband)
		  - General strength training devices
		  - Electrotherapy (ultrasound, shortwave, TENS)
		  - Heat/Cold treatment
		2. Muscle reconditioning on training devices *(n=45)*
		  - 1 hour sessions in groups of 2-3, strength training, or
		3. Low-impact aerobics *(n=41)*
		• Twice a week for 3 months
			Physical measures:
			• Flexion relaxation response (FRR)
			Also
			• Extensor fatigue (Biering-Sorensen)
			• Isometric strength trunk muscles
			• Lumbar ROM using CA 6000 (flexion/extension, lateral flexion, rotation)
			Measurement method
			• Surface electromyography (sEMG)
			Health outcomes:
			• VAS
			• RMDQ
			• FABQ
			• Coping Strategy questionnaire (Rosenstiel, AK et al., 1983)
				• Baseline, 13 weeks, 26 weeks

Marshall 2008 *Source:* • Not stated *Type of condition:* • Chronic LBP *Number of subjects:* • N=50 post intervention (60 at baseline)	*Inclusion Criteria* • CLBP non-specific > 3 months duration *Exclusion Criteria* • Severe postural abnormality or neuromuscular disorder; previous diagnosis of pathology (confirmed by MRI or radiography), which would contraindicate exercise or spinal manipulation; manipulative treatment in the last 3 months; or previous participation in a specific abdominal stabilisation training program.	16-week intervention period, with initial 4-week self-selected Rx (manip vs non-manip) followed by a 12-week randomised selection into either: *Intervention group (n=24)* • Specific swiss ball exercise group – weekly training, over 12 weeks *Comparison group (n=26)* • General home-based exercise group with 3 clinic-based check-up sessions	***Physical measures:*** • Feed-forward activation of transverse abdominal wall (Transversus Abdominis (TA) & Internal Oblique muscles (IO)) • FRR (T12/L1 and L4/5) ***Measurement method*** • sEMG ***Health outcomes***: • ODI	• Baseline, 4 weeks, 8 weeks, 16 weeks, 56 weeks
O'Sullivan 1997 &1998 *Source:* • General and specialist medical clinics, pain management and physiotherapy clinics *Type of condition:* • Chronic LBP in people with spondylolisthesis or spondylolysis *Number of subjects:* • N=42 post intervention, (44 at baseline)	*Inclusion Criteria* • Aged between 16 and 49 years • Spondylolithesis or spondylolysis • Chronic LBP • Clinical presentation attributed to the spondylolithesis or spondylolysis by the treating medical specialist *Exclusion Criteria* • Previous specific stabilising exercise • Diagnosed psychological illness • Inadequate English comprehension • Previous spinal surgery • Diagnosed inflammatory joint disease • Presence of neurologic signs	*Intervention group (n=21)* • Weekly sessions over 10 weeks • Training of deep abdominal muscles using abdominal drawing in manoeuvre + co-activation of lumbar Multifidi proximal to pars defect • Progression by limb loading then adding functional position *Comparison group (n=21)* • As directed by medical practitioner (mixed approach – general exercise, heat, massage, ultrasound, trunk curl exercises)	***Physical measures:*** • sEMG (ratio of Internal Oblique (IO) to Rectus Abdominus (RA) activity) *Also* • Lx ROM (using Cybex digital inclinometer) • Hip ROM ***Measurement method*** • sEMG ***Health outcomes***: • McGill pain questionnaire • ODI	• Baseline, 10 weeks,13 weeks, 26 weeks, 52 weeks
Ritvanen 2007 *Source:* • Community sourced via advertisement *Type of condition:* • Chronic LBP *Number of subjects:* • N=61 at post intervention and at baseline	*Inclusion Criteria* • Aged between 20 and 60 years • Chronic LBP +/- leg pain but not below knee • LBP present on at least half of the days in a 12-month period in a single episode or in multiple episodes. *Exclusion Criteria* • Severe neurologic, metabolic, or cardiovascular diseases, back surgery, mental diseases, a major structural abnormality (e.g. kyphoscoliosis), any compensable disease, pregnancy.	*Intervention group (n=33)* • Traditional bone setting therapy (manual whole body therapy, aiming to abolish mal positions, relax muscles, improve body symmetry) x 5 fortnightly sessions over 10 weeks *Comparison group (n=28)* • Physical therapy included massage, therapeutic stretching, trunk stabilisation exercise, and exercise therapy.	***Physical measures:*** • FRR *Also* • Trunk ROM (finger to floor, and lateral flexion) ***Measurement method*** • sEMG ***Health outcomes***: • ODI • Depression questionnaire • VAS • Patient satisfaction	• Baseline, 14 weeks

Vasseljen 2010	Inclusion Criteria	Intervention group (n=30)	Physical measures:	• Baseline, 8-10 weeks post intervention
Source: • Community sourced via advertisement and from medical practitioners *Type of condition:* • Chronic LBP *Number of subjects:* • N= 85 post intervention (109 at baseline)	• Men and women aged between 18 and 60years with non-specific, chronic LBP, and pain at presentation between 2 and 8 on an 11-point Numeric Rating Scale (NRS 0-10). *Exclusion Criteria* • Prior spinal surgery, radiating pain below the knee, other chronic pain, neurological or rheumatic diagnosis, compensable injuries, sick-leave due to LPB for more than a year at presentation, pregnancy, or insufficient comprehension of Norwegian language.	Low load, specific exercises - Ultrasound-guided abdominal hollowing exercise (progresses to functional movements) *Comparison groups (n=29)* 1. High load specific exercise - Sling exercises 2. General exercises *(n=26)* All groups had x1 session per week for 8 weeks	• Transversus Abdominis Ratio (maximum thickness on contraction divided by thickness at rest) vs Internal Oblique ratio and External Oblique ratio • Lateral slide of Transversus Abdominis (mm) *Measurement method* • Ultrasound *Health outcomes*: • Numerical rating scale (NRS) • Oswestry Disability Index • Fear avoidance belief questionnaire • BMI	

[1]Chronic LBP defined as LBP> 3 months, [2]VAS = visual analogue scale (0-10 or 0-100) for pain intensity, [3] American College of Sports Medicine Guidelines for exercise testing and prescription.

9.3. Appendix C: Excluded studies and reasons for exclusions from Laird et al (2012)

Study	Reason for exclusion (studies may have also met other exclusion criteria)
Aleksiev et al. (Aleksiev, A et al., 1996)	No specific movement pattern, artificially induced movement alteration = difficult to generalise
Ali. (Ali, AA, 2002)	Not obtainable (PhD not published)
Bakhtiary et al. (Bakhtiary, AH et al., 2005)	No specific measure of muscle activation, no pattern assessment
Boston et al. (Boston, JR et al., 1995)	Non-painful control group
Brox et al. (Brox, JI et al., 2003)	Surgical intervention
Childs et al, (Childs, J et al., 2004)	No specific measure of muscle activation, no pattern assessment
Celestini et al. (Celestini, M et al., 2005)	No data for muscle activation, movement pattern or posture
Curnow et al. (Curnow, D et al., 2009)	No data for health outcome
Danneels et al. (Danneels, L et al., 2001)	No data for health outcome
Derman et al. (Derman, KL et al., 1995)	Non-painful control group
Dwornik et al. (Dwornik, M et al., 2009)	No pattern of muscle activation, movement or posture measured (resting tone or gross ROM only)
Ferreira et al. (Ferreira, ML et al., 2007)	No specific measure of muscle activation, no pattern assessment
Goldby et al. (Goldby, LJ et al., 2006)	No specific measure of muscle activation, no pattern assessment
Harrison et al. (Harrison, D et al., 2002)	Unequal outcome measurement between control and treatment groups
Harrison et al. (Harrison, DE et al., 2005)	Unequal outcome measurement between control and treatment groups
Hoffman et al. (Hoffman, SL et al., 2011)	No pain or activity data
Huber et al. (Huber, J et al., 2011)	No pattern of muscle activation, movement or posture measured (gross ROM, EMG only)
Karimi et al. (Karimi, N et al., 2009)	Whole body movement, no health outcome measurement
Koumantakis et al. (Koumantakis, GA et al., 2005)	Whole body movement – no assessment of patterns
Leinonen et al. (Leinonen, V et al., 2000)	Whole body movement – no assessment of patterns
Lewis et al. (Lewis, JS et al., 2005)	Whole body movement – no assessment of patterns
Lu et al. (Lu, WW et al., 2001)	Non-painful control group

Luoto et al. (Luoto, S et al., 1998)	Non-painful control group
Marshall et al. (Marshall, P. et al., 2008)	Not a controlled trial
Mooney et al. (Mooney, V et al., 1997)	Non-painful control group
Neblett et al. (Neblett, R et al., 2010)	Not randomised or controlled trial
Nouwen. (Nouwen, A, 1983)	No data for health outcome
Petrofsky et al. (Petrofsky, JS et al., 2008)	Whole body movement – no assessment of patterns
Poosanthanasam et al. (Poosanthanasarn, N et al., 2005a)	No data for health outcome
Poosanthanasam et al. (Poosanthanasarn, N et al., 2005b)	No data for health outcome
Roche-Leboucher et al. (Roche-Leboucher, GMD et al., 2011)	No specific measure of motor control, no pattern assessment
Stuge et al. (Stuge, B et al., 2004)	No pattern of muscle activation, movement or posture measured (ASLR measured by subjective assessment)
Sung. (Sung, PS et al., 2003)	Whole body movement – no assessment of patterns
Suni et al. (Suni, J et al., 2006)	Whole body movement – no assessment of patterns
Tsao et al. (Tsao, H et al., 2010)	No data for health outcome

BMC
Musculoskeletal Disorders

RESEARCH ARTICLE　　　　　　　　　　　　　　　　　　　**Open Access**

Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis

Robert A Laird[1,5*], Jayce Gilbert[2], Peter Kent[3,4] and Jennifer L Keating[1]

Abstract

Background: Clinicians commonly examine posture and movement in people with the belief that correcting dysfunctional movement may reduce pain. If dysfunctional movement is to be accurately identified, clinicians should know what constitutes normal movement and how this differs in people with low back pain (LBP). This systematic review examined studies that compared biomechanical aspects of lumbo-pelvic movement in people with and without LBP.

Methods: MEDLINE, Cochrane Central, EMBASE, AMI, CINAHL, Scopus, AMED, ISI Web of Science were searched from inception until January 2014 for relevant studies. Studies had to compare adults with and without LBP using skin surface measurement techniques to measure lumbo-pelvic posture or movement. Two reviewers independently applied inclusion and exclusion criteria, and identified and extracted data. Standardised mean differences and 95% confidence intervals were estimated for group differences between people with and without LBP, and where possible, meta-analyses were performed. Within-group variability in all measurements was also compared.

Results: The search identified 43 eligible studies. Compared to people without LBP, on average, people with LBP display: (i) no difference in lordosis angle (8 studies), (ii) reduced lumbar ROM (19 studies), (iii) no difference in lumbar relative to hip contribution to end-range flexion (4 studies), (iv) no difference in standing pelvic tilt angle (3 studies), (v) slower movement (8 studies), and (vi) reduced proprioception (17 studies). Movement variability appeared greater for people with LBP for flexion, lateral flexion and rotation ROM, and movement speed, but not for other movement characteristics. Considerable heterogeneity exists between studies, including a lack of detail or standardization between studies on the criteria used to define participants as people with LBP (cases) or without LBP (controls).

Conclusions: On average, people with LBP have reduced lumbar ROM and proprioception, and move more slowly compared to people without LBP. Whether these deficits exist prior to LBP onset is unknown.

Keywords: Low back pain, Movement disorders, Posture, Range of movement, Lordosis, Proprioception

Background

Observation of lumbo-pelvic movement and posture is a basic component of the physical examination of people with low back pain (LBP) [1-4] partly due to a common belief held by clinicians that identifying and correcting movement/postural aberration can improve pain and activity limitation [2,5,6]. Examination of lumbo-pelvic movement typically includes basic kinematic assessments, such as range of movement (ROM) and posture. It may also include higher order kinematics such as temporal and sequential patterns during physiological movements, proprioception, muscle activation patterns, postural sway and/or complex functional movements such as walking or lifting. If clinicians aim to 'normalise' dysfunctional movement, they need an empirical basis for (i) differentiating between normal and dysfunctional movement, and (ii) determining whether correction of dysfunctional movement might reduce pain and activity limitation. Measurement of movement and posture has been problematic in typical clinical settings due to limitations (practicality, accuracy,

* Correspondence: robert.laird@monash.edu
[1]Department of Physiotherapy, Monash University, PO Box 527, Frankston, VIC 3199, Australia
[5]7 Kerry Rd, Warranwood, Melbourne, VIC 3134, Australia
Full list of author information is available at the end of the article

comprehensiveness, reliability) of simple measurement tools such as goniometers, tape measures and inclinometers [7]. Advances in technology are creating new opportunities, available for use in typical clinical settings, that measure comprehensive information about the relationship between movement/posture and pain [8-10].

Measurements reported in studies of lumbo-pelvic kinematics, such as ROM, vary considerably. This variability may be due to differences in measurement instruments or methods [11], biological differences in true range of movements, or errors in measurements. Intolo [12], in a systematic review into the effect of age on ROM, performed a meta-analysis of mean scores for lumbar ROM for 20-29 year olds. Across studies, the lowest reported group mean score for flexion was $24 \pm 7°$ [13] while the highest was $75 \pm 10°$ [14]. Similarly, mean scores for extension ranged from $13 \pm 8°$ [13] to $41 \pm 10°$ [15]. These large differences between studies are unlikely to be due to biological differences alone. Milosavljevic et al. [13] provided ROM estimates using a photographic method, Russell et al. [14] used an Isotrak system and Fitzgerald et al. [15] used a tape-measure (Schober) method [16]; such method differences are likely to account for a large proportion of observed differences. Similar variation is seen for axial rotation and lateral flexion movements. Extreme variations in reported ROM measurements limit confidence in clinical interpretations or treatment decisions based on measurements of an individual.

A search for reviews on what is known about typical movement in people with and without LBP identified one review on postural sway [17], and one review on age-related changes to lumbar spine ROM [12]. The qualitative review on postural sway, reported that 14 of 16 included papers concluded that people with LBP have greater postural sway excursion when compared to people without LBP. The review on age-related change to lumbar ROM reported a reduction in ROM associated with increasing age but did not include people with LBP and did not report mean ROM data. No reviews were found comparing people with and without LBP on any other movement characteristics. Therefore, we designed this review to systematically investigate and compare typical lumbo-pelvic movement differences between people with and without LBP, focusing on ROM, movement sequence and speed, a movement related measure of proprioception (positioning/re-positioning accuracy), pelvic tilt angles (in standing and sitting), and segmental body contributions to movement (lumbar versus hip contributions). We also compared differences in variability between the two groups.

Methods

Study selection: inclusion and exclusion criteria

For inclusion in the review, studies had to (i) assess adults >17 years; (ii) use non-invasive measurement systems (i.e. did not use measurements such as X-rays, CT scans); (iii) apply the same procedures to measure people with low back +/-leg pain (LBP group) and people without LBP (NoLBP group), (iv) measure at least one of lumbar lordosis, lumbar range of motion (ROM), speed/acceleration/timing of lumbar +/- hip movement, pelvic tilt angle (as measured by a line drawn from anterior to posterior superior iliac spines with an angle formed relative to horizontal, measured in sitting or standing), pelvic tilt ROM (defined as a range from maximum anterior tilt to maximum posterior tilt), usual sitting pelvic tilt position (i.e. relative to full anterior tilt), lumbar compared with hip contributions to ROM, lumbo-pelvic proprioceptive position/re-position accuracy; (v) report appropriate measurement means (or other point estimates) and variance estimates or data that enable estimation of these values. In order to fully survey published research on lumbo-pelvic movement, no specific definitions of back pain or control (NoLBP) groups were required but the definitions of LBP group, pain intensity and NoLBP group within each study were extracted. Studies were excluded if they (i) included people who had lumbar surgery in the previous 12 months; (ii) reported that subjects had fracture, neurological conditions, metabolic disease, neoplasm, or scoliosis; (iii) measured only whole body movement such as distance from finger-tip-to-floor or (iv) reported insufficient data, e.g. did not report measures of variability. Lead authors were contacted to obtain additional data as required.

Data sources

Eight electronic databases (MEDLINE, Cochrane Central Register of Controlled Trials (Central), EMBASE, AMI, CINAHL, Scopus, AMED, ISI Web of Science) were searched from inception until January 2014 using a broad search strategy based on relevant medical subject heading (MeSH) terms [18] (see Additional file 1). The search yield was initially screened for eligibility by one reviewer (RL) on title and abstract to remove duplicates and clearly unrelated articles. Following this, two reviewers (RL and JG) independently identified potentially relevant articles based on title and abstract. Full text articles were retrieved and checked for compliance with inclusion and exclusion criteria. References of potentially relevant reports were reviewed for additional papers. Consensus by discussion was then reached on article inclusion. Where disagreement occurred, a third reviewer (JK) was included and discussion continued until consensus was achieved. A flow diagram of the study selection process based on PRISMA recommendations [19] is seen in Figure 1.

Data extraction and study quality assessment

A checklist for data extraction was developed based on those used in a similar review [12] and published quality

```
┌─────────────────────────────────────────────┐
│ Electronic Database search:                   │
│  • Medline, Cochrane, AMED (via Ovid)  7137   │
│  • Embase                               816   │
│  • Aust. Med. Index                      92   │
│  • Cinahl                               570   │
│  • Scopus                              4496   │
│  • ISI Web of Science                  4165   │
│                                               │
│                          Total 17276          │
└─────────────────────────────────────────────┘
```

9813 articles after
duplicates removed

13 additional articles identified through other sources → 9826 articles screened by title and abstract → 9740 articles excluded

86 full text articles retrieved and assessed for eligibility →

articles excluded:
- Single cohort studies (30)
- Differentiation between LBP and normal subjects poor (1)
- Post surgical subjects (1)
- Insufficient data (5)
- Hip movement only (1)
- Participants < 17 years (3)

45 articles (43 studies) included in review

35 studies included in meta-analysis

Figure 1 Flow diagram of study inclusion.

assessment tools [20-22]. The following study details were extracted: participant age, sex, and source characteristics, inclusion/exclusion criteria, training of testers (profession, experience), measurement methods and procedures (instrument used, instructions to participants, position of testing), the movement characteristics assessed (e.g. range, speed, relative contributions of body segments), pain/function measures, measurements for those with and without back pain (e.g. means, standard deviations). A quality assessment tool, using a similar approach to Mieritz [23], was constructed to determine how each study accounted for possible sources of bias, and if the study provided details on: (i) study population (age, sex, BMI, source), (ii) participant LBP (chronicity, +/- leg pain, specific versus non-specific, pain intensity and activity limitation scores), (iii) measurement procedures (i.e. detail that would enable accurate replication of the experiment, instrument description, standardised movement instructions, movement process description e.g. fixed or free pelvis), (iv) blinding of assessors to the presence of back pain (yes/no), and (vi) whether the same assessment procedures were applied to participants with and without back pain (see Additional file 2). Two reviewers independently extracted data, compared results and resolved differences through discussion.

Data synthesis and analysis

Study details were extracted and summarised (Additional files 3 and 4). For each comparison, standardised mean differences (SMD) between groups with and without LBP were calculated using Revman software [24]. Pooled estimates of overall differences were calculated by meta-analysis of studies that measured a kinematic characteristic using comparable methods. For example studies on flexion ROM were included in a meta-analysis if subjects were standing using angular measurement but excluded if subjects were in other positions (i.e. four point kneeling) or if linear/distance measurements were used. Reasons for exclusion from meta-analysis are found in Additional file 3. A random effects model was used for pooling where fixed effects modeling indicated statistical heterogeneity of the data (Mantel-Haenszel method), as determined by chi-squared and I^2 statistics; otherwise the results of fixed effects modeling was reported [25,26].

We also planned to explore the within-group variability in each measured movement characteristic. To estimate whether variability for each movement characteristic differed between groups with and without LBP, a coefficient of variation (CoV) [27] (standard deviation in measurements divided by the group mean) was calculated for each movement parameter using those studies included in the relevant meta-analysis. CoVs were averaged after weighting for sample size. Differences between groups were examined by creating a ratio of weighted averages where ratios >1 indicate greater variability for those with LBP and ratios <1 indicate greater variability for those without LBP. Significant differences in pooled CoVs were examined by estimating 95% confidence intervals for observed ratios. The correlation (Pearson's r) between effect size and study quality was calculated using STATA (version 12, Stata Corp, College Station, Texas USA).

Results
Search yield
The search identified 17,276 potentially relevant articles with 13 articles identified from bibliographies of related articles or other sources. Following screening of title and abstract, full texts of 86 articles were retrieved. Forty three studies (45 articles) met the inclusion criteria [28-70]. The study selection process is shown in Figure 1. A summary of included studies can be seen in Additional file 3. A list of studies retrieved in full text and subsequently excluded, and reasons for exclusion, are available from the first author on request.

Types of studies found
Included studies were grouped in categories: lordosis [31,32,38,47-49,57,58], range of movement (ROM) [29,30, 34,37-42,44,47,50-54,56-59,69,71], relative hip and lumbar contribution to trunk flexion/extension [34,40,50,52,61,71], pelvic angle/relative position and ROM [31,32,57,58], speed/acceleration of lumbar movement [28,34,37,39,41, 42,50,71], and proprioception (repositioning accuracy) [33,35,45,46,53,55,60-68,70,72]. Additional file 4 summarises the characteristics of included studies.

Definition of LBP and NoLBP groups
Case definition (LBP) Of the 43 studies included, 48% provide no detail on diagnostic criteria, 37% defined their LBP participants as non-specific, and the remaining 15% used either a Quebec [73] or a movement based classification (see Additional file 5 for details). Fifty-six percent reported pain intensity scores.

Control definition (NoLBP) A definition of control participants was provided by 60% of the 43 studies. Those definitions were highly variable, ranging from vague descriptions such as 'no current pain' (16%), six-months

(14%), 12-months (14%) or 24-months (7%) pain free to 'no LBP ever' (9%).

Quality assessment
Table 1 lists the domains identified as potential sources of bias in the included studies and the percentage compliance with each item. No studies attempted blinding of assessors to group status, and only one study reported standardizing instructions to participants. The potential influence of study quality on reported differences between groups was examined for all groups. There was no significant correlation observed between total quality assessment scores and the magnitude of SMDs in measurements for those with and without LBP (r = 0.03), There was also no significant difference between individual items of quality assessment and the size of SMD. Results for individual studies are available in Additional file 5.

Movement characteristics
Lordosis
A meta-analysis of eight studies comparing lumbar lordosis angle in people with and without LBP when standing is presented in Figure 2. Most studies reported small, non-significant differences between groups. The pooled difference (SMD = 0.01, 95% CI -0.09 to 0.11, p = 0.89) was not significant. A post-hoc meta-analysis of three studies that compared genders indicated that women had greater lordosis angles than men (SMD = 0.92, 95% CI 0.8 to 1.05, p < 0.01).

Range of motion (ROM)
Meta-analyses of 26 ROM studies consistently found reduced range of movement of the lumbar spine in people with LBP. Figures 3, 4, 5 and 6 summarise the findings for flexion, extension, lateral flexion and rotation meta-analysis. Where studies measured bilateral movement, i.e. left and right rotation, weighted means and standard deviations were averaged. In some included studies, measurements from a single group without LBP were compared with a number of LBP groups, such as men and women or acute and chronic LBP. As the observed differences may not satisfy the statistical assumption of independence required for meta-analysis [74], the sample size of these groups without LBP used in the meta-analysis were divided by the number of comparisons made. Means and standard deviations (SD) are in degrees of movement.

Lumbar spine versus hip contribution to flexion/extension
Six studies examined the relative lumbar and hip contribution to flexion movements, five [34,50,52,61,71] during forward flexion, and one [40] returning from a fully flexed position. Four of five studies investigating forward flexion found no significant difference between those with and

Table 1 Quality assessment summary (see Additional files 2 and 5 for item decision rules and scores for each included study)

	Quality assessment domains	Percentage of studies scoring yes
	Selection bias	
1.	Was the study population adequately described?	57%
2.	Where both groups drawn from the same population?	39%
3.	Were both groups comparable for age, sex, BMI/weight	54%
4.	Was pain intensity and/or activity limitation described for LBP group?	56%
5.	Was an attempt made to define back pain characteristics?	34%
	Measurement and outcome bias	
6.	Did the method description enable accurate replication of the measurement procedures	90%
7.	Was the measurement instrument adequately described?	95%
8.	Was a system for standardising movement instructions reported?	37%
9.	Were assessors trained in standardised measurement procedure?	2%
10.	Did the same assessors test those with and without back pain	17%
11.	Were assessors blinded as to which group subjects were in?	0%
12.	Was the same assessment procedure applied to those with and without back pain?	93%
	Data presentation	
13.	Were between-group statistical comparisons reported for at least one key outcome	94%

without LBP when comparing lumbar with hip contribution (ratio) to flexion ROM *at end range*. A non-significant but consistent effect favored reduced lumbar (compared with hip) contribution to flexion (Figure 7) for those with LBP (SMD = -0.21, 95% CI -0.52 to 0.09, p = 0.17). Three studies [34,40,52] found significant differences in the '*through-range*' contribution of lumbar movement. Esola et al. [34] (SMD = -0.86, 95% CI -1.51 to -0.22) and Porter et al. [52] (SMD = -0.71 95% CI -1.43 to 0.00) both found significant reductions of lumbar contribution to mid-range flexion but not at end range. McClure et al. [40] found a greater contribution of the lumbar spine during mid-range return from the fully flexed position (relative extension) (SMD = 0.95 95% CI 0.10 to 1.81).

Pelvic tilt angle, relative position and tilt range

Three studies (four articles) examined usual pelvic tilt angle in standing [31,32,57,58]. No significant differences

were found between people with or without LBP for any study (see Table 1 for details). A small, non-significant but consistent effect favouring greater anterior pelvic tilt in people with LBP was evident when studies were pooled in meta-analysis (see Figure 8). Only Day et al. [32] compared differences between groups with and without LBP in full anterior and posterior tilt positions, and found a significant difference for maximum anterior tilt angle (higher angle for people with LBP) :SMD = 0.73 (0.09 to 1.35, p = 0.02), but not maximum posterior tilt angle: SMD = 0.09 (-0.53 to 0.7, p = 0.78)).

Speed/Acceleration

Seven studies measured speed [34,37,39,43,50,71,75] and one measured acceleration [28]. Data on lumbar flexion speed/acceleration differences between groups with and without LBP were combined in meta-analysis (Figure 9). A large, significant effect of slower movement in the
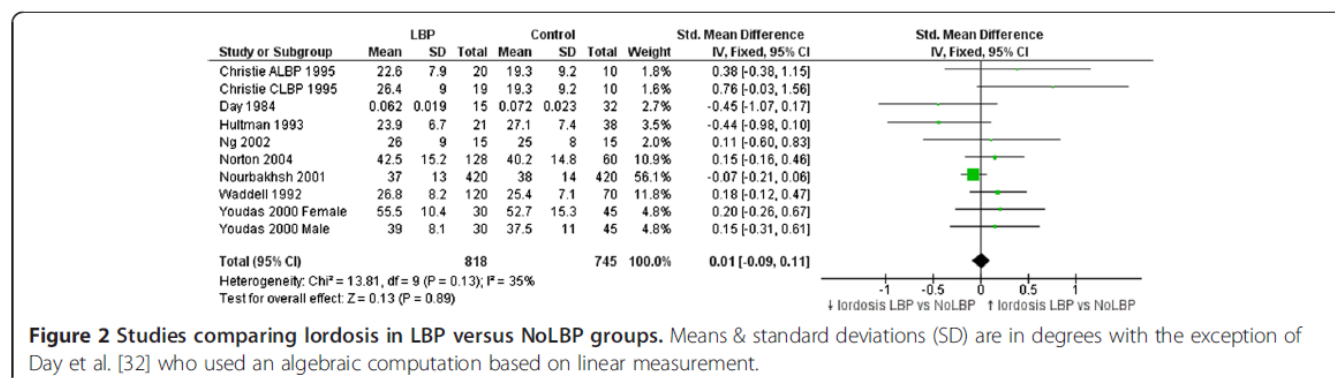
Figure 2 Studies comparing lordosis in LBP versus NoLBP groups. Means & standard deviations (SD) are in degrees with the exception of Day et al. [32] who used an algebraic computation based on linear measurement.

Study or Subgroup	LBP Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Crosbie 2013	48	20	19	50	20	19	5.8%	-0.10 [-0.73, 0.54]
Esola 1996	40.3	14.1	20	43	10.3	21	5.9%	-0.22 [-0.83, 0.40]
Hidalgo 2012	69.4	16.8	25	92.2	14.9	25	5.9%	-1.41 [-2.04, -0.79]
Hultman 1993	41	7	21	48.7	8	38	6.1%	-0.99 [-1.56, -0.43]
Marras 1995	31.4	13.4	339	36	15	171	7.4%	-0.33 [-0.51, -0.14]
McGregor 1997	49.3	17.3	138	56.7	11.2	203	7.3%	-0.53 [-0.75, -0.31]
McGregor 2000	32	19	15	73	13	15	4.5%	-2.45 [-3.43, -1.47]
Mellin 1990 Female	43	8	29	40	8	19	6.0%	0.37 [-0.21, 0.95]
Mellin 1990 Male	27	6	26	27	8	29	6.3%	0.00 [-0.53, 0.53]
Ng 2002	51	13	15	50	10	15	5.5%	0.08 [-0.63, 0.80]
Porter 1997	57.5	9.1	15	68.6	9.2	17	5.3%	-1.18 [-1.94, -0.42]
Tsai 2010	56	12	16	55	11	16	5.6%	0.08 [-0.61, 0.78]
Waddell 1992	48.7	14.9	120	42.4	10.7	70	7.1%	0.46 [0.17, 0.76]
Wong 2004 LBP & +ive SLR	33.2	8.7	24	61.9	9.9	10	4.1%	-3.10 [-4.17, -2.02]
Wong 2004 LBP only	29.8	11.9	21	61.9	9.9	10	4.2%	-2.76 [-3.82, -1.71]
Youdas 2000 Female	20.7	8.9	30	23	10.1	45	6.5%	-0.24 [-0.70, 0.23]
Youdas 2000 Male	28.6	6.6	30	31	5.7	45	6.5%	-0.39 [-0.86, 0.08]
Total (95% CI)			903			768	100.0%	**-0.62 [-0.94, -0.29]**

Heterogeneity: Tau² = 0.36; Chi² = 126.26, df = 16 (P < 0.00001); I² = 87%
Test for overall effect: Z = 3.75 (P = 0.0002)

Figure 3 Flexion ROM meta-analysis.

LBP group was evident (SMD -1.46 95% CI -1.96 to -1.02, p < .01).

Proprioception

Fifteen studies [33,35,45,46,53,55,60,62-68,70,76] measured position/reposition accuracy as a measure of lumbar spine proprioception (see Additional files 3, 4 and 6 for details). Twelve studies [35,45,46,53,60,62-64,68-70,76] measured absolute error in re-positioning accuracy and were included in meta-analysis. One study measured the number of trials required to achieve accurate re-positioning [33], one measured motion detection, [55] one measured ability to achieve a described position [67] and two measured motion precision [65,66] but were excluded from meta-analysis as data were not comparable. A consistent, large and significant reduction in ability to accurately re-position the spine at pre-specified angles for people with LBP compared to those without LBP is shown in Figure 10 (SMD = 1.04, 95% CI 0.64 to 1.45, p < 0.01). The studies included in this review using different types of assessments that precluded meta-analysis also found significant differences indicating reduced proprioception in the LBP group (26,55). Descarreaux et al. [33] tested if LBP subjects (divided into two groups according to normal or slow speed of force production on isometric resistance) compared to subjects without LBP, could accurately place the lumbar spine into various flexion angles. They determined that although both LBP and control groups demonstrated similar re-positioning accuracy, the LBP subgroup that developed slow isometric force (n = 9 of 16) required significantly more practice to achieve this (SMD = 1.87, 95% CI 0.89 to 2.85, p < 0.01). Taimela et al. [55] reported a significant reduction in the ability of people with chronic LBP to detect change in lumbar position when compared to a group without LBP but did not include data on variability required for meta-analysis. Field et al. [67] demonstrated reduced accuracy for people with LBP in achieving a demonstrated position in flexion when compared to people without LBP (SMD = 1.66, 95% CI 0.82 to 2.42, p < 0.01). Willigenberg et al. [65,66] also identified reduced accuracy in both motion control, (SMD = 1.14, 95% CI 0.39 to 1.89, p < 0.01) and motion tracking in people with LBP (SMD = 1.08, 95% CI 0.32 to 1.84, p < 0.01).

A summary of standardised mean differences, across all the kinematic characteristics investigated, is shown in Table 2.

Differences in variability between groups

Table 3 presents a summary of the within group variability in movements pooled across studies. Significantly greater variability for people with LBP compared to people

Study or Subgroup	LBP Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Hultman 1993	10.3	4.6	21	17.2	5.6	38	8.2%	-1.29 [-1.88, -0.71]
McGregor 1997	16.8	8.3	138	23.8	18.2	203	12.1%	-0.47 [-0.68, -0.25]
McGregor 2000	8	8	15	20.5	7	15	5.8%	-1.62 [-2.46, -0.78]
Mellin 1990 Female	43	8	29	40	8	19	8.2%	0.37 [-0.21, 0.95]
Mellin 1990 Male	39	8	26	44	9	29	8.6%	-0.58 [-1.12, -0.04]
Ng 2002	16	7	15	19	8	15	6.8%	-0.39 [-1.11, 0.34]
Tsai 2010	26	7	16	28	8	16	7.1%	-0.26 [-0.96, 0.44]
Waddell 1992	18.4	8	120	26.5	8.9	70	11.2%	-0.97 [-1.28, -0.66]
Wong 2004 LBP & +ive SLR	14.9	7.7	24	15.5	7.4	10	6.7%	-0.08 [-0.81, 0.66]
Wong 2004 LBP only	12.7	5.9	21	15.5	7.4	10	6.5%	-0.43 [-1.19, 0.34]
Youdas 2000 Female	56	12	30	56.5	10.4	45	9.5%	-0.04 [-0.51, 0.42]
Youdas 2000 Male	42.7	8.8	30	50.1	9.2	45	9.3%	-0.81 [-1.29, -0.33]
Total (95% CI)			485			515	100.0%	**-0.54 [-0.81, -0.27]**

Heterogeneity: Tau² = 0.15; Chi² = 37.67, df = 11 (P < 0.0001); I² = 71%
Test for overall effect: Z = 3.91 (P < 0.0001)

Figure 4 Extension ROM meta-analysis.

Study or Subgroup	LBP Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Barrett 1999	24.5	6	23	28	5	31	10.1%	-0.63 [-1.19, -0.08]
Crosbie 2013	23	11	19	28	13	19	9.5%	-0.41 [-1.05, 0.24]
Marras 1995	3.5	2.8	339	3.3	2.7	171	12.1%	0.07 [-0.11, 0.26]
McGregor 1997	25.7	7.6	138	31.9	6.4	203	12.0%	-0.90 [-1.12, -0.67]
Mellin 1990	42.2	11.4	55	43.8	10	48	11.2%	-0.15 [-0.54, 0.24]
Ng 2002	29.5	5.5	15	31	15	55	10.0%	-0.11 [-0.68, 0.46]
Tsai 2010	37	6.5	16	41	6	16	9.0%	-0.62 [-1.34, 0.09]
Waddell 1992	22.7	7.6	120	29.4	6.5	70	11.6%	-0.92 [-1.23, -0.62]
Wong 2004 LBP & +ive SLR	11.8	4.3	24	23.7	5.4	10	7.2%	-2.51 [-3.48, -1.53]
Wong 2004 LBP only	12.8	4.7	21	23.7	5.4	10	7.4%	-2.15 [-3.10, -1.21]
Total (95% CI)			**770**			**633**	**100.0%**	**-0.73 [-1.14, -0.33]**

Heterogeneity: Tau² = 0.34; Chi² = 88.86, df = 9 (P < 0.00001); I² = 90%
Test for overall effect: Z = 3.55 (P = 0.0004)

Less movt LBP vs NoLBP   More movt LBP vs NoLBP

Figure 5 Lateral flexion ROM meta-analysis.

without LBP was observed on four of the eight measures: flexion, lateral flexion, rotation and speed/acceleration.

Discussion

This review summarised the results of studies of lumbo-pelvic kinematics for people with and without LBP. Although the results will be unsurprising to most clinicians, it is the first review to meta-analyse and quantify the clinical observation that, on average, people with LBP have reduced lumbar ROM, move more slowly and have reduced proprioception compared to with those without LBP.

The review highlights the highly heterogenous nature of available studies, with six of nine meta-analyses indicating significant between study heterogeneity in results. Possible sources of heterogeneity between study outcomes include differences in definitions of back pain, control characteristics, LBP intensity, and instruments and methods for measuring movements. This heterogeneity confounds secondary analyses such as the influence of pain intensity on observed differences between people with and without LBP.

The lack of detail or standardized definition for control subjects is also problematic. For example, it is hypothetically possible that altered movement characteristics occur as a result of a LBP episode and persist after pain resolves. If this is the case, people that were pain free but with persistent altered movements, would have been eligible as control subjects for many of the included studies, provided the episode had been prior to the pain-free time period required for that study. This would have diluted differences between the groups. Similarly, it is not known if certain 'aberrant' movement characteristics exist prior to the onset of LBP and are risk factors for an episode of LBP, in which case these characteristics may have also been present in people classified in the included studies as control subjects.

No studies attempted to blind assessors to group type, and a general absence of procedural standardization, such as movement instruction or assessor consistency, exposes studies to the potential for random or systematic error. However, the relative consistency of the direction of results across studies adds credibility to the findings of this review, and observed effects appear large enough to be visible despite potential study limitations.

Lordosis

Lordosis angle does not differentiate people with and without LBP. A similarly wide range of group means were reported for those with LBP (23° to 56°) and without LBP (19° to 53°). This variability might be associated with the six different measurement methods, but may also reflect biological differences in sample ethnicity [77], age [78] and gender [49,57,58]. Increasing age has been associated with reduced lordosis in the sixth decade [78-80] and on average, females have a greater lordosis than males [49,58,80]. Four studies included only males [31,32,38,47] and it is perhaps understandable that these studies found the four lowest average lordosis angles. However, this variability in lordosis appears similar for people with and without LBP. Therefore, lumbar lordosis when measured

Study or Subgroup	LBP Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Crosbie 2013	12	6	19	12	6	19	8.7%	0.00 [-0.64, 0.64]
Hidalgo 2012	50.6	12.4	25	61.6	10.3	25	9.4%	-0.95 [-1.54, -0.36]
Marras 1995	31.7	13.4	339	36	15	171	15.5%	-0.31 [-0.49, -0.12]
McGregor 1997	25.8	7.65	138	31.9	6.4	203	15.0%	-0.88 [-1.10, -0.65]
Ng 2002	27.5	6.5	15	30.5	10	15	7.7%	-0.35 [-1.07, 0.38]
Pope 1985	2.99	0.74	215	3.34	0.71	106	14.8%	-0.48 [-0.71, -0.24]
Sung 2012	14.58	5.5	15	10.06	4.5	15	7.3%	0.88 [0.12, 1.63]
Tsai 2010	43	5	16	47	7	16	7.8%	-0.64 [-1.35, 0.07]
Wong 2004 LBP & +ive SLR	7.3	3.7	24	12.2	4.6	10	6.9%	-1.20 [-2.00, -0.41]
Wong 2004 LBP only	9	3.4	21	12.2	4.6	10	7.0%	-0.82 [-1.60, -0.03]
Total (95% CI)			**827**			**590**	**100.0%**	**-0.49 [-0.76, -0.22]**

Heterogeneity: Tau² = 0.12; Chi² = 36.25, df = 9 (P < 0.0001); I² = 75%
Test for overall effect: Z = 3.54 (P = 0.0004)

Less movement LBP vs NLBP   More movement LBP vs NLBP

Figure 6 Rotation ROM meta-analysis.

Study or Subgroup	LBP Mean	SD	Total	NoLBP Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Esola 1996	0.64	0.25	20	0.65	0.29	21	24.6%	-0.04 [-0.65, 0.58]
Kim 2013 Extension LBP	0.8	0.7	14	0.9	0.7	8	12.2%	-0.14 [-1.01, 0.73]
Kim 2013 Flexion LBP	1.2	0.6	17	0.9	0.7	8	12.7%	0.46 [-0.39, 1.31]
Porter 1997	0.99	0.32	15	1.19	0.32	17	18.2%	-0.61 [-1.32, 0.10]
Wong 2004 LBP & +ive SLR	0.85	0.52	21	0.91	0.24	10	16.2%	-0.13 [-0.88, 0.62]
Wong 2004 LBP only	0.7	0.31	24	0.91	0.24	10	16.0%	-0.70 [-1.46, 0.06]
Total (95% CI)			**111**			**74**	**100.0%**	**-0.21 [-0.52, 0.09]**

Heterogeneity: Chi² = 5.57, df = 5 (P = 0.35); I² = 10%
Test for overall effect: Z = 1.37 (P = 0.17)

↓Lx vs Hip for LBP group   ↑Lx vs Hip for LBP group

Figure 7 Meta-analysis of studies investigating the relative contributions of lumbar versus hip ROM through the range of trunk flexion. Means (and SDs) are ratios of lumbar to hip movement. Zero represents equal lumbar to hip contribution to trunk flexion, numbers <0 indicate less lumbar compared with hip movement while numbers >0 indicate more hip than lumbar movement.

using surface techniques, does not, on average, appear to discriminate between people with and without LBP.

Range and speed of motion

Clinicians commonly use ROM [81] to assist in identifying patterns of dysfunction, and to monitor change. ROM has been extensively studied by invasive and non-invasive methods, but non-invasive measurement is better suited to routine clinical assessment. This review included 20 studies that compared ROM for those with and without LBP using skin-surface measurement. The pooled sample was large enough to be confident in the finding that people with LBP have reduced average lumbar ROM compared to those without LBP. The mean ROM reported for people without LBP is so variable that it has little reference value e.g. (considering all studies) flexion: min = 23°, max = 92°; extension: min = 15°, max = 56°, lateral flexion: min = 3°, max = 44°; rotation: min = 3°, max = 62°. Large variations between studies suggest differences beyond those explained by biological variation and implicate method differences. Using flexion ROM as an example, 14 studies used nine different measurement devices ranging in sophistication from simple handheld inclinometers and flexible rulers to opto-electronic devices. Youdas [57,58] used a flexible rule measurement technique (mean lumbar flexion angle = 23 ± 10°) while Hidalgo [37] used an opto-electronic system (92 ± 15°); both studies used similar inclusion criteria, and the same starting position. Other method processes may also contribute to differences: two studies assessed range in sitting, 10 in relaxed standing, and two used some form of restricted movement (harness or fixed pelvic position). Based on these findings, normative data may have limited relevance to a clinical

environment unless the same measurement methods used to obtain published data are also used in the clinical setting where they are applied. The lack of clarity about similarity between study populations and method details makes the use of pooled group-level estimates of movements, such as mean flexion ROM, unwise. However, these between-study differences did not obscure consistent within-study findings; eight of 14 studies of flexion demonstrated significantly less lumbar flexion for those with LBP and only one study found that lumbar flexion was significantly greater for those with LBP. These findings of large between study differences in measurements, and consistent within study differences between those with and without LBP, are similar for the other movements analysed in this review.

Lower movement speed is commonly seen in people with LBP, so it is unsurprising to observe in our review that those with LBP demonstrated significantly slower speeds when the eight included studies were pooled in meta-analysis. Reduced speed of lumbar movement has been linked to fear of movement and has also been shown to persist after recovery [82].

Lumbar versus hip contribution to movement

Clinicians have reported assessing the relative contribution of lumbar and hip joints (during flexion and extension movements) to assist in determining subgroups within the LBP population that require specific treatment strategies [83,84]. This review identified six studies that measured patterns and relative contributions to trunk flexion from the lumbar spine and hip joints, often described as 'lumbo-pelvic rhythm'. Data could be pooled for four studies (six comparisons) evaluating ROM of

Study or Subgroup	LBP Mean	SD	Total	No LBP Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Christie CLBP 1995	12.8	8.8	19	10.7	9	20	17.4%	0.23 [-0.40, 0.86]
Day 1984	11	8.1	15	9.5	5.1	32	18.3%	0.24 [-0.38, 0.85]
Youdas 2000 Female	25	7.3	30	22.8	7.6	45	32.1%	0.29 [-0.17, 0.76]
Youdas 2000 Male	14.9	7.7	30	13.8	4.5	45	32.3%	0.18 [-0.28, 0.64]
Total (95% CI)			**94**			**142**	**100.0%**	**0.24 [-0.03, 0.50]**

Heterogeneity: Chi² = 0.11, df = 3 (P = 0.99); I² = 0%
Test for overall effect: Z = 1.76 (P = 0.08)

↓anterior tilt LBP group   ↑ anterior tilt LBP group
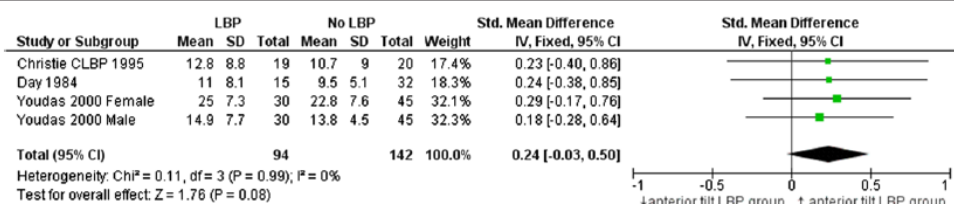
Figure 8 Meta-analysis of studies comparing pelvic tilt angle in neutral standing.

Study or Subgroup	LBP Mean	SD	Total	No LBP Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Aluko 2011	150.2	108.7	10	234.9	154.8	10	8.3%	-0.61 [-1.51, 0.29]
Esola 1996	35.94	11.07	20	41.78	12.58	21	11.9%	-0.48 [-1.10, 0.14]
Hidalgo 2012	117.6	34.3	25	159.3	40.8	25	12.3%	-1.09 [-1.69, -0.49]
Marras 1995	47.7	28.8	339	92	49	171	18.5%	-1.20 [-1.40, -1.00]
McGregor 1997	21.2	11.5	138	31.9	12.5	203	18.1%	-0.88 [-1.11, -0.66]
McGregor 2000	15	11	15	54	18	15	7.4%	-2.54 [-3.54, -1.55]
Paquet 1994	62	13	10	75	15	10	8.0%	-0.89 [-1.82, 0.04]
Wong 2004 LBP & +ive SLR	4.6	2.3	24	17.4	8.7	10	7.6%	-2.50 [-3.47, -1.52]
Wong 2004 LBP only	5.8	2.9	21	17.4	8.7	10	7.9%	-2.09 [-3.02, -1.15]
Total (95% CI)			602			475	100.0%	-1.24 [-1.58, -0.90]

Heterogeneity: Tau² = 0.15; Chi² = 30.02, df = 8 (P = 0.0002); I² = 73%
Test for overall effect: Z = 7.10 (P < 0.00001)

Slower movt LBP vs NoLBP   Faster movt LBP vs NoLBP
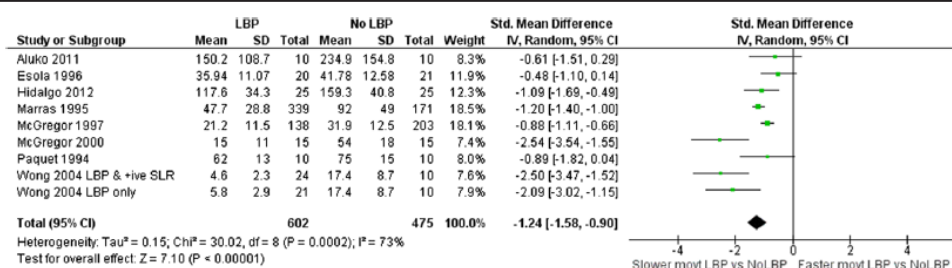
Figure 9 Forest plot of speed differences between LBP and NoLBP groups (original units are deg/sec or deg/sec²).

lumbar and hip contribution at end-range flexion. A typical pattern of lumbar versus hip movement for both groups showed less lumbar and greater hip ROM at end-range flexion, with small, non-significant differences of reduced lumbar contribution for the LBP group when compared to people without LBP.

However relative contributions of lumbar spine and hip to ROM may be less important than patterns of when and how movement takes place. Nelson-Wong et al. [84] recently reported that the relative timing of hip and lumbar movement when arising from a fully flexed position differentiated between people who do or do not develop back pain after two hours of standing. People who developed pain used a lumbar > hip initiation of movement (spine moves first followed by pelvic/hip movement) strategy on arising from the flexed position while non-pain developers used a hip > lumbar strategy (p = 0.03). This finding is supported by McClure et al. [40], Esola et al. [34] and Porter et al. [52] who all reported relatively greater lumbar through-range contribution in people with LBP on flexion movement. It may be that people with LBP can be subgrouped by lumbo-pelvic rhythm. For example, Kim et al. [61] examined lumbo-pelvic rhythm by comparing two subgroups of people with LBP to a group of people without LBP. One subgroup had pain provoked by flexion/rotation activities and the other by extension/rotation activity. The flexion-aggravated group had significantly greater lumbar contribution to flexion

compared to the normal and extension groups. The extension-aggravated group on the other hand had a significant pattern of reduced lumbar contribution to flexion. Lumbar versus hip contributions to movement, particularly flexion, appear to have clinical relevance and warrant further exploration.

Pelvic tilt angle, position and range

Extreme (end-range) pelvic tilt angle in standing and sitting has been linked to back pain [85,86] but with limited evidence. Clinical interventions aiming to modify pelvic tilt angle to achieve more neutral positions are based on the assumption that there is a relationship between position and pain. There are few studies that explore the relationship between LBP and typical pelvic tilt range (from full anterior to full posterior tilt) and the relative position of pelvic tilt angle during sitting and standing in people with and without LBP. This review found no differences when pooling data from three studies that compared standing pelvic tilt angle in people with and without LBP. Similarly, Astfalk et al. [85] found no differences in average lumbar flexion angle in sitting (reflecting pelvic tilt position) when comparing adolescents with and without LBP (125.3 ± 19.8° vs 130.6° ± 15.7 respectively). However significant differences were observed for lumbar flexion angle when adolescents with LBP were sub-grouped based on direction of movement that provoked pain. The flexion-provoked pain group had a significantly greater

Study or Subgroup	LBP Mean	SD	Total	No LBP Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Brumagne 2000 Sitting	4.3	1	23	1.6	0.6	21	6.6%	3.18 [2.27, 4.09]
Georgy 2011 Sitting	7.3	2.8	30	2.8	0.9	15	7.4%	1.88 [1.14, 2.62]
Gill 1998 Standing	6.7	5	20	4.5	3.4	20	8.0%	0.50 [-0.13, 1.13]
Hidalgo 2013 Sitting	4.3	2.6	10	1.8	2	10	6.4%	1.03 [0.09, 1.98]
Koumantakis 2002 Standing	5.5	3.5	62	3.7	1.8	18	8.5%	0.56 [0.02, 1.09]
Lee 2010 Sidelaying	1.3	1.1	24	0.7	0.4	24	8.2%	0.71 [0.13, 1.30]
Newcomer 2000a Standing	2.1	1.2	20	2.7	2	20	8.0%	-0.36 [-0.98, 0.27]
Newcomer 2000b Standing	5.1	2.2	20	3.4	2.2	20	7.9%	0.76 [0.11, 1.40]
OSullivan,K 2013 Sitting	11.5	6.4	15	5.1	3.6	15	7.2%	1.20 [0.41, 1.99]
OSullivan,P 2003 Sitting	1.7	0.8	15	1.1	0.6	15	7.4%	0.83 [0.08, 1.58]
Sheeran 2012 Sitting	7.7	4.1	90	1.8	0.8	17	8.3%	1.55 [0.99, 2.11]
Sheeran 2012 Standing	6.3	3.7	90	1.9	1	18	8.5%	1.28 [0.74, 1.81]
Tsai 2010 Standing	3.2	1.5	16	2.1	0.9	16	7.5%	0.87 [0.14, 1.60]
Total (95% CI)			435			229	100.0%	1.04 [0.64, 1.45]

Heterogeneity: Tau² = 0.43; Chi² = 57.03, df = 12 (P < 0.00001); I² = 79%
Test for overall effect: Z = 5.06 (P < 0.00001)

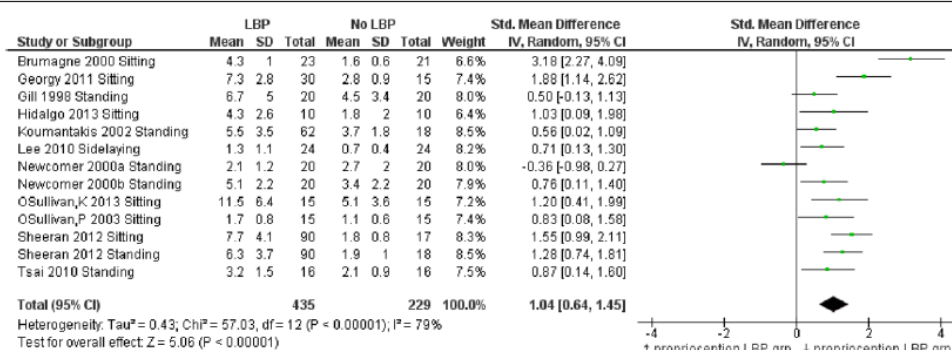↑ proprioception LBP grp   ↓ proprioception LBP grp

Figure 10 Forest plot of position/reposition differences (raw scores in degrees) comparing LBP and NoLBP groups.

Table 2 Summary of pooled standardized mean differences

Position and movement differences between people with and without LBP (number of studies included in meta-analysis)	Standardised mean difference (95% CI) for all studies suitable for meta-analysis
Lordosis*, n = 8	0.01 (-0.09 to 0.11), p = 0.89
Flexion**, n = 14	-0.62 (-0.94 to -0.29), p < 0.01
Extension**, n = 9	-0.54 (-0.81 to -0.27), p < 0.01
Lateral Flexion**, n = 9	-0.73 (-1.14 to -0.33), p < 0.01
Rotation**, n = 9	-0.49 (-0.76 to -0.22), p = 0.04
Lumbar versus Hip end-range flexion ROM**, n = 4	-0.21 (-0.52 to 0.09), p = 0.17
Pelvic tilt angle in standing[†], n = 3	0.24 (-0.03 to 0.50), p = 0.08
Speed/Acceleration[‡], n = 8	-1.24 (-1.58 to -0.90), p < 0.0001
Proprioception (re-position accuracy)[§], n = 12	1.04 (0.64 to 1.45), p < 0.0001

*Positive numbers indicate larger lordosis for the LBP group, **negative numbers indicate reduced ROM for the LBP group, † positive numbers indicate larger anterior tilt, ‡negative numbers indicate reduced speed of movement for the LBP group, §positive numbers indicate greater error rate in re-positioning (reduced proprioception).

lumbar angle (135.6 ± 16.9°, p < 0.05) compared to those without LBP while the extension-provoked pain group had a significantly smaller lumbar angle (113.5 ± 16.3°, p < 0.05) when compared to those without LBP. Sub-grouping of a LBP population based on the relationship of aggravating activities and direction of painful movement may demonstrate associations between back pain and pelvic tilt angle/relative position.

Proprioception

Our meta-analysis of studies measuring one aspect of proprioception (absolute error during re-positioning trials) demonstrated a significant and large loss of re-positioning accuracy in the LBP group. The implications of reduced proprioception are that people with LBP are less 'movement-aware' with potentially reduced postural control. This is consistent with a recent systematic review on another aspect of proprioception, postural sway, by Ruhe et al. [17] who found that greater sway excursion and speed were present in people with LBP compared to people without back pain.

Differences in variability between people with and without LBP

Our assessment of differences in variability between people with and without LBP for nine movement characteristics demonstrated significantly greater variability for four movement characteristics: flexion, lateral flexion and rotation ROM, and speed of movement. There were no significant differences in variability for lordosis, extension ROM, lumbar versus hip contribution to movement or proprioception. It is not clear if the greater variability seen in the LBP group is clinically meaningful (10% difference in average variability estimates) but it raises a question of whether postures or activities performed using extremes of certain movement (e.g. excessive or restricted movement) may predispose people to LBP.

This review examined differences in group means for people with and without LBP. Given the high variability seen between studies, the small between-group differences compared with the high within-group differences, and the greater variability on some movement characteristics seen in the LBP group, these findings cast some doubt

Table 3 Differences between the LBP and NoLBP in within-group variability on each movement characteristic and ratios of n-weighted mean coefficients of variation

Movement Characteristic (number of comparisons)	LBP group coefficient of variation	N	NoLBP group coefficient of variation	n	Ratio of coefficients of variation (95% CI)
Lordosis angle (8)	33.1%	818	34.6%	745	0.96 (0.83 to 1.10)
Flexion ROM* (18)	35.1%	913	26.8%	778	**1.31 (1.13 to 1.51)**
Extension ROM (12)	41.5%	485	47.2%	515	0.88 (0.76 to 1.01)
Lateral flexion ROM (9)	52.6%	751	40.1%	614	**1.31 (1.17 to 1.48)**
Rotation ROM* (10)	34.3%	827	28.7%	590	**1.20 (1.02 to 1.40)**
Lumbar vs hip (6)	51.2%	111	42.8%	74	1.2 (0.87 to 1.65)
Speed/acceleration* (8)	54.7%	602	42.6%	475	**1.28 (1.13 to 1.46)**
Proprioception (13)	53.9%	435	53.2%	229	1.01 (0.87 to 1.18)

*Statistically significant differences (95% CIs > 1.0) are bolded.

on whether an assessment of movements without reference to pain provides evidence of dysfunction at an individual patient level. The results neither endorse nor disqualify the role of movement assessment for (i) determining the relationship between movement and pain in individual patients, or (ii) monitoring changes in movement characteristics as a means of monitoring progress in individual patients and as an indication of the likelihood of their improvement [87]. Key questions also remain, including (a) are deficits such as reduced proprioception, reduced ROM and speed of movement a result or a cause of LBP, and (b) are these deficits present prior to the development of LBP?

Strengths and limitations

The strengths of this systematic review are the comprehensive search, the breadth of the movement characteristics included in the analysis, and that screening and data extraction were independently performed by two reviewers. In addition, the review only included studies that assessed people with and without LBP using the same within-study method, thereby removing method differences as an explanation for observed within-study differences.

The review also has limitations. We treated the data for people with LBP as if they were measurements of a homogenous group. It is possible that sub-grouping by using the relationship of pain to movement may increase the clinical utility of particular measurements. The findings in this review do not inform clinicians about whether changes in ROM, movement speed or proprioception will produce better outcomes, or if changes in movement characteristics precede the onset of LBP or predispose to future recurrences. In addition, due to an absence of translation resources, only articles published in English were included and this may introduce a language, cultural and/or publication bias. To maximize the number of included studies, we did not place any restrictions on the criteria used to define pain cases versus pain-free controls. However, our broad inclusion criteria are likely to have weakened, rather than strengthened differences seen between people with and without LBP, and in the included studies, higher pain intensities had a weak correlation with increased differences between the these groups.

Conclusion

This paper systematically summarised what is known about differences in measurements of lumbo-pelvic movement for people with and without back pain. It included 43 studies and synthesised information on six movement characteristics: lordosis, ROM, lumbar versus hip contribution, pelvic tilt, speed and proprioception. The results show that compared to people without pain, on average, people with LBP display (i) no difference in their lordosis

angle (8 studies), (ii) a reduction of lumbar ROM in all directions of movement (26 studies), (iii) no difference in lumbar versus hip ROM contribution to full flexion (4 studies), (iv) no difference in pelvic tilt angle in standing (3 studies), (v) slower lumbar movement (7 studies), and (vi) poorer proprioception on position-reposition accuracy (15 studies). There is greater movement variability for people with LBP for flexion, lateral flexion and rotation ROM, and speed of movement, but this is not apparent for other movement characteristics. So put simply, when considered collectively, people with LBP have reduced lumbar ROM, move more slowly and have reduced proprioception compared with people without low back pain.

Additional files

> **Additional file 1:** Search strategy medline.
>
> **Additional file 2:** Quality assessment.
>
> **Additional file 3:** Categories of included studies.
>
> **Additional file 4:** Characteristics of included studies.
>
> **Additional file 5:** Quality assessment.
>
> **Additional file 6:** Summary of studies examining lumbar proprioception.

Abbreviations
LBP: Low back pain; ROM: Range of motion; SMD: Standardised mean difference; NoLBP: People without low back pain.

Author details
[1]Department of Physiotherapy, Monash University, PO Box 527, Frankston, VIC 3199, Australia. [2]Peak MSK Physiotherapy, Suite 4/544 Hampton St, Hampton, VIC 3188, Australia. [3]Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense 5230, Denmark. [4]Research Department, Spine Centre of Southern Denmark, Lillebaelt Hospital, Institute of Regional Health Services Research, University of Southern Denmark, Middelfart 5500, Denmark. [5]7 Kerry Rd, Warranwood, Melbourne, VIC 3134, Australia.

References
1. Liebenson C: *Rehabilitation of the spine: a practitioner's manual.* 2nd edition. Baltimore: Lippincott Williams & Wilkins; 2007.
2. Sahrmann S: *Diagnosis and treatment of movement impairment syndromes.* St Louis: Mosby Inc; 2002.

3. McKenzie R, May S: *Lumbar Spine, Mechanical Diagnosis and Therapy.* 2nd edition. Waikanae, New Zealand: Spinal Publications Ltd; 2003.
4. Maitland GD: *Vertebral Manipulation.* 5th edition. London: Butterworths; 1986.
5. O'Sullivan PB: **Diagnosis and classification of chronic low backpain disorders: Maladaptive movement and motor control impairments as underlying mechanism.** *Man Ther* 2005, **10**:242–255.
6. Ikeda K, McGill S: **Can altering motions, postures, and loads provide immediate low back pain relief: A study of 4 cases investigating spine load, posture, and stability.** *Spine* 2012, **37**(23):E1469–E1475.
7. Chen SP, Samo DG, Chen EH, Crampton AR, Conrad KM, Egan L, Mitton J: **Reliability of three lumbar sagittal motion measurement methods: surface inclinometers.** *J Occup Environ Med* 1997, **39**(3):217–223.
8. Ha TH, Saber-Sheikh K, Moore AP, Jones MP: **Measurement of lumbar spine range of movement and coupled motion using inertial sensors - A protocol validity study.** *Man Ther* 2012, **18**(1):87–91.
9. Ribeiro DC, Sole G, Abbott JH, Milosavljevic S: **Cumulative postural exposure measured by a novel device: a preliminary study.** *Ergonomics* 2011, **54**(9):858–865.
10. Van Hoof W, Volkaerts K, O'Sullivan K, Verschueren S, Dankaerts W: **Comparing lower lumbar kinematics in cyclists with low back pain (flexion pattern) versus asymptomatic controls – field study using a wireless posture monitoring system.** *Man Ther* 2012, **17**(4):312–317.
11. Mannion A, Troke M: **A comparison of two motion analysis devices used in the measurement of lumbar spinal mobility.** *Clin Biomech* 1999, **14**(9):612–619.
12. Intolo P, Milosavljevic S, Baxter DG, Carman AB, Pal P, Munn J, Intolo P, Milosavljevic S, Baxter DG, Carman AB, Pal P, Munn J: **The effect of age on lumbar range of motion: a systematic review.** *Man Ther* 2009, **14**(6):596–604.
13. Milosavljevic S, Milburn PD, Knox BW: **The influence of occupation on lumbar sagittal motion and posture.** *Ergonomics* 2005, **48**(6):657–667.
14. Russell P, Pearcy MJ, Unsworth A: **Measurement of the range and coupled movements observed in the lumbar spine.** *Rheumatology (Oxford)* 1993, **32**(6):490–497.
15. Fitzgerald G, Wynveen K, Rheault W, Rothschild B: **Objective assessment with establishment of normal values for lumbar spinal range of motion.** *Phys Ther* 1983, **63**(11):1776–1781.
16. Schober P: **The lumbar vertebral column and back ache.** *Munch Med Wochenschr* 1937, **84**:336.
17. Ruhe A, Fejer R, Walker B: **Center of pressure excursion as a measure of balance performance in patients with non-specific low back pain compared to healthy controls: a systematic review of the literature.** *Eur Spine J* 2011, **20**(3):358–368.
18. The NCBI Handbook (internet): 2nd edition. Betheseda (MD): National Centre for Biotechnology Information (US); 2013. http://www.ncbi.nlm.nih.gov/mesh.
19. Moher D, Liberati A, Tetzlaff J, Altman D: **TPG: preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement.** *Ann Intern Med* 2009, **151**(4):264–269.
20. Hollingworth W, Medina S, Lenkinski R, Shibata D, Bernal B, Zurakowski D, Comstock B, Jarvik J: **Interrater reliability in assessing quality of diagnostic accuracy studies using the QUADAS tool.** *Acad Radiol* 2006, **13**(7):803–810.
21. Whiting PF, Weswood ME, Rutjes AW, Reitsma JB, Bossuyt PN, Kleijnen J: **Evaluation of QUADAS, a tool for the quality assessment of diagnostic accuracy studies.** *BMC Med Res Methodol* 2006, **6**(9). doi:10.1186/1471-2288-1186-1189.
22. Bossuyt PM, Reitsma JB, Bruns DE, Gatsonis CA, Glatsonis PP, Irwig LM, Moher D, Rennie D, de Vet HC: **Towards complete and accurate reporting of studies of diagnostic accuracy: The STARD Initiative.** *Radiology* 2003, **226**:24–28.
23. Mieritz R, Bronfort G, Kawchuk G, Breen A, Hartvigsen J: **Reliability and measurement error of 3-dimensional regional lumbar motion measures: a sytematic review.** *J Manipulative Physiol Ther* 2012, **35**(8):645–656.
24. The Cochrane Collaboration: **Review Manager (RevMan) (computer program).** Version 5.2. Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration; 2012.
25. Higgins J, Green S: **Cochrane Handbook for Systematic Reviews of Interventions, Version 5.1.0.** In *The Cochrane Collaboration.* 2011. Available from http://www.cochrane-handbook.org.
26. Higgins J, Thompson S, Deeks J, Altman DG: **Measuring inconsistency in meta-analyses.** *Br Med J (Clin Res Ed)* 2003, **327**(9):557–560.
27. Koopmans L, Owen D, Rosenblatt J: **Confidence intervals for the coefficient of variation for the normal and log normal distributions.** *Biometrika* 1964, **51**:25–32.
28. Aluko A, DeSouza L, Peacock J: **Evaluation of trunk acceleration in healthy individuals and those with low back pain.** *Int J Ther Rehabil* 2011, **18**(1):18–25.
29. Barrett CJ, Singer KP, Day R: **Assessment of combined movements of the lumbar spine in asymptomatic and low back pain subjects using a three-dimensional electromagnetic tracking system.** *Man Ther* 1999, **4**(2):94–99.
30. Boline P, Keating J, Haas M, Anderson A: **Interexaminer reliability and discriminant validity of inclinometric measurement of lumbar rotation in chronic low-back pain patients and subjects without low-back pain.** *Spine* 1992, **17**(3):335–338.
31. Christie HJ, Kumar S, Warren SA: **Postural aberrations in low back pain.** *Arch Phys Med Rehabil* 1995, **76**(3):218–224.
32. Day JW, Smidt GL, Lehmann T: **Effect of pelvic tilt on standing posture.** *Phys Ther* 1984, **64**(4):510–516.
33. Descarreaux M, Blouin J-S, Teasdale N: **Repositioning accuracy and movement parameters in low back pain subjects and healthy control subjects.** *Eur Spine J* 2005, **14**(2):185–191.
34. Esola MA, McClure PW, Fitzgerald GK, Siegler S: **Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain.** *Spine* 1996, **21**(1):71–78.
35. Gill K, Callaghan M: **The measurement of lumbar proprioception in individuals with and without low back pain.** *Spine* 1998, **23**(3):371–377.
36. Gomez TT: **Symmetry of lumbar rotation and lateral flexion range of motion and isometric strength in subjects with and without low back pain.** *J Orthop Sports Phys Ther* 1994, **19**(1):42–48.
37. Hidalgo B, Gilliaux M, Poncin W, Detrembleur C: **Reliability and validity of a kinematic spine model during active trunk movement in healthy subjects and patients with chronic non-specific low back pain.** *J Rehabil Med* 2012, **44**(9):756–763.
38. Hultman G, Nordin M, Saraste H, Ohlsen H: **Body composition, endurance, strength, corss-sectional area, and desnity of MM erector spinae in men with and without low back pain.** *J Spinal Disord* 1993, **6**:114–123.
39. Marras W, PaParnianpour M, Ferguson S, Kim J, Crowell R, Bose S, Simon S: **The classification of anatomic- and symptom-based low back disorders using motion measure models.** *Spine* 1995, **20**(23):2531–2546.
40. McClure P, Esola M, Schreier R, Siegler S: **Kinematic analysis of lumbar and hip motion while rising from a forward, flexed position in patients with and without a history of low back pain.** *Spine* 1997, **22**(5):552–558.
41. McGregor A, McCarthy I, Dore C, Hughes S: **Quantitative assessment of the motion of the lumbar spine in the low back pain population and the effect of different spinal pathologies on this motion.** *Eur Spine J* 1997, **6**(5):308–315.
42. McGregor A, McCarthy I, Hughes S: **Motion characteristics of the lumbar spine in the normal population.** *Spine* 1995, **20**(22):2421–2428.
43. McGregor AH, Hughes SP: **The effect of test speed on the motion characteristics of the lumbar spine during an A-P flexion-extension test.** *J Back Musculoskelet Rehabil* 2000, **14**(3):99–104.
44. Mellin G: **Decreased joint and spinal mobility associated with low back pain in young adults.** *J Spinal Disord* 1990, **3**(3):238–243.
45. Newcomer K, Laskowski E, Yu B, Larson D, An K: **Repositioning error in low back pain: Comparing trunk repositioning error in subjects with chronic low back pain and control subjects.** *Spine* 2000, **25**(2):245–250.
46. Newcomer KL, Laskowski ER, Yu B, Johnson JC, An KN: **Differences in repositioning error among patients with low back pain compared with control subjects.** *Spine* 2000, **25**(19):2488–2493.
47. Ng JK, Richardson CA, Kippers V, Parnianpour M, Ng JKF, Richardson CA, Kippers V, Parnianpour M: **Comparison of lumbar range of movement and lumbar lordosis in back pain patients and matched controls.** *J Rehabil Med* 2002, **34**(3):109–113.
48. Norton B, Sahrmann S, Van DL: **Differences in Measurements of Lumbar Curvature Related to Gender and Low Back Pain.** *J Orthop Sports Phys Ther* 2004, **34**(9):524–534.
49. Nourbakhsh MR, Moussavi SJ, Salavati M: **Effects of lifestyle and work-related physical activity on the degree of lumbar lordosis and chronic low back pain in a Middle East population.** *J Spinal Disord* 2001, **14**(4):283–292.
50. Paquet N, Malouin F, Richards C: **Hip-spine movement interaction and muscle activation patterns during sagittal trunk movements in low back pain patients.** *Spine* 1994, **15**(5):596–603.

51. Pope M, Bevins T, Wilder D, Frymoyer J: The relationship between anthropometric postural, muscular, and mobility characteristics of males aged 18-55. *Spine* 1985, **10**:644–648.

52. Porter JL, Wilkinson A: Lumbar-hip flexion motion. A comparative study between asymptomatic and chronic low back pain in 18- to 36-year-old men. *Spine* 1997, **22**(13):1508–1513. discussion 1513-1504.

53. Sheeran L, Sparkes V, Caterson B, Busse-Morris M, van Deursen R: Spinal position sense and trunk muscle activity during sitting and standing in nonspecific chronic low back pain: classification analysis. *Spine* 2012, **37**(8):E486–E495.

54. Sung PS, Park W-H, Kim YH: Three-dimensional kinematic lumbar spine motion analyses of trunk motion during axial rotation activities. *J Spinal Disord Tech* 2012, **25**(3):E74–E80.

55. Taimela S, Kankaanpaa M, Luoto S: The effect of lumbar fatigue on the ability to sense a change in lumbar position. A controlled study. *Spine* 1999, **24**(13):1322–1327.

56. Waddell G, Somerville D, Henderson I, Newton M: Objective clinical evaluation of physical impairment in chronic low back pain. *Spine* 1992, **17**(6):617–628.

57. Youdas JW, Garrett TR, Egan KS, Themeau TM: Lumbar lordosis and pelvic inclination in adults with chronic low back pain. *Phys Ther* 2000, **80**(3):261–275.

58. Youdas JW, Garrett TR, Harmsen S, Suman VJ, Carey JR: Lumbar lordosis and pelvic inclination of asymptomatic adults. *Phys Ther* 1996, **76**(10):1066–1081 (1030 ref).

59. Crosbie J, de Faria Negrao Filho R, Nascimento DP, Ferreira P: Coordination of spinal motion in the transverse and frontal planes during walking in people with and without recurrent low back pain. *Spine* 2013, **38**(5):E286–E292.

60. Hidalgo B, Gobert F, Bragard D, Detrembleur C: Effects of proprioceptive disruption on lumbar spine repositioning error in a trunk forward bending task. *J Back Musculoskel Rehabil* 2013, **26**(4):381–387.

61. Kim MH, Yi CH, Kwon OY, Cho SH, Cynn HS, Kim YH, Hwang SH, Choi BR, Hong JA, Jung DH: Comparison of lumbopelvic rhythm and flexion-relaxation response between 2 different low back pain subtypes. *Spine* 2013, **38**(15):1260–1267.

62. Lee AS, Cholewicki J, Reeves NP, Zazulak BT, Mysliwiec LW: Comparison of trunk proprioception between patients with low back pain and healthy controls. *Arch Phys Med Rehabil* 2010, **91**(9):1327–1331.

63. O'Sullivan K, Verschueren S, Van Hoof W, Ertanir F, Martens L, Dankaerts W: Lumbar repositioning error in sitting: Healthy controls versus people with sitting-related non-specific chronic low back pain (flexion pattern). *Man Ther* 2013, **18**(6):526–532.

64. O'Sullivan PB, Burnett A, Floyd AN, Gadsdon K, Logiudice J, Miller D, Quirke H: Lumbar repositioning deficit in a specific low back pain population. *Spine* 2003, **28**(10):1074–1079.

65. Willigenburg NW, Kingma I, Hoozemans MJM, van Dieen JH: Precision control of trunk movement in low back pain patients. *Hum Mov Sci* 2013, **32**(1):228–239.

66. Willigenburg NW, Kingma I, van Dieen JH: Precision control of an upright trunk posture in low back pain patients. *Clin Biomech* 2012, **27**(9):866–871.

67. Field E, Abdel-Moty E, Loudon J: The effect of back injury and load on ability to replicate a novel posture. *J Back Musculoskelet Rehabil* 1997, **8**(3):199–207.

68. Koumantakis GA, Winstanley J, Oldham JA: Thoracolumbar proprioception in individuals with and without low back pain: intratester reliability, clinical applicability, and validity. *J Orthop Sports Phys Ther* 2002, **32**(7):327–335.

69. Tsai Y, Sell T, Smoliga J, Myers J, Learman K, Lephart S: A comparison of physical characteristics and swing mechanics between golfers with and without a history of low back pain. *J Orthop Sports Phys Ther* 2010, **40**(7):430–438.

70. Georgy E: Lumbar repositioning accuracy as a measure of proprioception in patients with back dysfunction and healthy controls. *Asian Spine J* 2011, **5**(4):201–207.

71. Wong TK, Lee RY, Wong TKT, Lee RYW: Effects of low back pain on the relationship between the movements of the lumbar spine and hip. *Hum Mov Sci* 2004, **23**(1):21–34.

72. Brumagne S, Cordo P, Lysens R, Verschueren S, Swinnen S: The role of paraspinal muscle spindles in lumbosacral position sense in individuals with and without low back pain. *Spine* 2000, **25**(8):989–994.

73. Spitzer W, Arsenault S, Abenhaim L, Dupuis M, Belanger A, Bloch R, Bombardier C, Cruess R, Duval-Hesler N, Laflamme J, Lamoureux G, LeBlanc F, Nachemson A, Wood-Dauphinee S, Drouin G, Page J, Lortie M, Suissa S, Salmi LR, Rossignol M, Bilodeau D, Blain J: Quebec Task Force on spinal disorders - Scientific approach to the assessment and management of activity-related spinal disorders - a monograph for clinicians. *Spine* 1987, **12**(7):1–59.

74. Marin-Martines F, Sanchez-Meca J: Averaging dependent effect sizes in meta-analysis: a coutionary note about procedures. *Span J Psychol* 1999, **2**(1):32–38.

75. McGregor A, McCarthy I, Hughes S: Lumbar spine motion during freestyle lifting and changes in this motion with time. *J Back Musculoskelet Rehabil* 1997, **9**(1):35–37.

76. Brumagne S, Lysens R, Spaepen A: Lumbosacral repositioning accuracy in standing posture: a combined electrogoniometric and videographic evaluation. *Clin Biomech* 1999, **14**(5):361–363.

77. Mosner EA, Bryan JM, Stull MA, Shippee R: A comparison of actual and apparent lumbar lordosis in black and white adult females. *Spine* 1989, **14**(3):310–314.

78. Gelb D, Lenke L, Bridwell K, Blanke K, McEnery K: An analysis of sagittal spinal alignment in 100 asymptomatic middle and older aged volunteers. *Spine* 1995, **20**(12):1351–1358.

79. Adams MA, Bogduk N, Burton K, Dolan P: *The Biomechanics of Back Pain*. 3rd edition. Edinburgh: Churchill Livingston; 2012.

80. Amonoo-Kuofi H: Changes in the lumbosacral angle, sacral inclination and the curvature of the lumbar spine during aging. *Acta Antatomica* 1992, **145**:373–377.

81. Kent PM, Keating JL, Taylor NF: Primary care clinicians use variable methods to assess acute nonspecific low back pain and usually focus on impairments. *Man Ther* 2009, **14**(1):88–100.

82. Thomas JS, France CR, Lavender SA, Johnson MR: Effects of fear of movement on spine velocity and acceleration after recovery from low back pain. *Spine* 2008, **33**:564–570.

83. O'Sullivan PB: 'Clinical instability' of the lumbar spine: its pathological basis, diagnosis and conservative management. In *Grieve's Modern Manual Therapy - The Vertebral Column*. 3rd edition. Edited by Boyling J, Jull G. Edinburgh: Churchill Livingstone; 2005.

84. Nelson-Wong E, Brendon A, Csepe D, Lancaster D, Callaghan JP: Altered muscle recruitment during extension from trunk flexion in low back pain developers. *Clin Biomech* 2012, **27**:994–998.

85. Astfalck RG, O'Sullivan PB, Straker LM, Smith AJ, Burnett A, Caneiro JP, Dankaerts W: Sitting postures and trunk muscle activity in adolescents with and without nonspecific chronic low back pain: an analysis based on subclassification. *Spine* 2010, **35**(14):1387–1395.

86. O'Sullivan PB, Mitchell T, Bulich P, Waller R, Holte J: The relationship beween posture and back muscle endurance in industrial workers with flexion-related low back pain. *Man Ther* 2006, **11**(4):264–271.

87. Hahne AJ, Keating JL, Wilson SC: Do within-session changes in pain intensity and range of motion predict between-session changes in patients with low back pain? *J Physiother* 2004, **50**(1):17–23.

9.5. Appendix E: Search Strategy Medline for Laird et al (2014)

Sample of Medline search strategy

#	Search Statement	Results
1	(Normative or normal or adult or in vivo).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]	5500580
2	(back pain or pain or lumbago or low back pain or LBP or spondylosis or lumbo-pelvic or lumbopelvic or pelvis or pelvic or vertebro-femoral or vertebrofemoral or trunk).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]	555926
3	(Skin-surface or skin or surface or surface-mounted or electronic or opto-electronic or inclinometer or inclinometry or goniometer or measurement or measurements or reliability or validity or strain gauge ORinertial or accelerometry or accelerometer).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]	2140465
4	(Movement or movements or movement pattern or movement patterns or pattern or flexibility or mobility or motion or motion analysis or lordosis or kinematic or kinematics or posture or postural or position or range of motion or range or flexion or extension or lateral flexion or sidebending or rotation or rhythm or proprioception or re-position or reposition or repositioning or re-positioning or temporal or timing or speed or velocity or acceleration or sitting or standing).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]	2562142
5	1 and 2 and 3 and 4	19229
6	limit 5 to english language	17853
7	limit 6 to humans	17180
8	(surg$ or fusion or decompression or laminectomy or discectomy or aneurysm or arter$ or fractur$ or injection$ or drug$ or pharmaceutical).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]	4718892
9	7 not 8	10164
10	(cervical or neck or ankle or knee or shoulder or elbow or hand or wrist).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]	783838
11	9 not 10	6749
12	(tumor$ or tumour$ or carcinoma or osteonecrosis or neoplasm$ or cancer$ or bone graft$).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]	2651122

13	11 not 12	6215
14	(osteoarthritis or effusion or ischiofemoral or acetabul$ or anteversion or retroversion or hip replacement or prosthe$).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]	312593
15	13 not 14	5951
16	(metabol$ or osteoporo$ or osteopen$ or aneurysm or injection$ or fusion or urinary).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]	2079392
17	15 not 16	5707
18	(urinary or rect$ or kidney or renal or nephro$ or pudendal).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]	1215521
19	17 not 18	5437
20	(scoliosis or scoliotic or idiopathic).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier]	94643
21	19 not 20	5324

9.6.   Appendix F: Quality assessment rules for Laird et al 2014

Criteria definition and decision rules

	Criteria	Decision rule
Selection bias		
1.	Was the study population adequately described?	Age (mean+SD, or range), sex (male vs female subjects), BMI (or weight) ±SD). All three variables must be included to score yes.
2.	Were both groups drawn from the same population?	People were from the same setting, e.g. people with and without back pain from a single setting such as a university, OR where they matched age/sex/BMI or weight case controls. If so score yes, if no or no data, score no.
3.	Were both groups comparable on age, sex, BMI/weight	Was a comparison made between groups on these parameters? Yes, if comparison made AND groups were comparable. No, if not comparable or no comparison made.
4.	Was pain intensity and/or activity limitation described for LBP group?	Score yes, if measured using a validated scale, such as a Visual Analogue Scale or Numeric Rating Scale for pain or the Oswestry Disability Index or Roland Morris Disability Questionnaire or similar.
5.	Was an attempt made to define back pain characteristics?	(i) Stage (acute/subacute/chronic) (ii) +/- leg pain? (iii) Information on specific vs non-specific diagnosis. Score yes, if at least two out of these three variables were covered.
Measurement and outcome bias		
6.	Did the method description enable accurate replication of the measurement procedures?	Description enables accurate replication of the measurement procedures (score yes).
7.	Was the measurement instrument adequately described?	Instrument used to measure described (score yes).
8.	Was a system for standardising movement instructions reported?	A system for standardising movement instructions is reported (score yes).
9.	Were assessors trained in standardised measurement procedure?	Yes, if report of training, or no, if no mention of training process.
10.	Did the same assessors test those with and without back pain?	If yes, then score yes. If no detail, score no.
11.	Were assessors blinded as to which group subjects were in?	If blinding attempted, was it evaluated and found to be successful (e.g. attempting to guess group assignment resulted in answers that could occur by chance alone).
12.	Was the same assessment procedure applied to those with and without back pain?	If there was any difference in procedure or measurement, then score no.
Data presentation		
13.	*Statistical analysis bias* The results of between-group statistical comparisons are reported for at least one key outcome	Yes or no.

14.	Point estimates and measures of variability are provided for at least one key outcome for those with and without back pain	Yes or no.

A "no" score indicates that no data or information were provided.

9.7. Appendix G: Categories of included studies in Laird et al (2014)

(✓ = included, ✓✓ = appropriate for meta-analysis)

	Author, Date	Lordosis in standing	Lumbar spine ROM (standing unless otherwise stated)				Pelvic tilt position or ROM	Hip versus lumbar contribution	Velocity/ Acceleration	Proprioception re-position accuracy	Data appropriate for meta-analysis (or reasons for not including)
			F	E	LF	Rot					
1.	Aluko, 2011								✓✓ F, E in standing		✓✓
2.	Barrett, 1999				✓✓						✓✓
3.	Boline, 1992					✓ (in 90º F)					position too different
4.	Brumagne 2000									✓✓ sitting	✓✓
5.	Christie, 1995	✓✓					✓ sitting, standing				✓✓
6.	Crosbie, 2013		✓✓		✓✓	✓✓ sitting					✓✓
7.	Day, 1984	✓✓					✓ supine, standing				✓✓
8.	Descarreaux, 2005									✓ standing	different method of measuring proprioception
9.	Esola, 1996		✓✓					✓✓	✓✓ F		✓✓
10.	Field, 1997									✓ standing	only study to use positioning rather than re-positioning approach
11.	Georgy, 2011									✓✓ sitting	✓✓
12.	Gill, 1998									✓✓ standing, 4-point kneeling	✓✓

No.	Study									
13.	Gomez, 1994				✓	✓				compared asymmetries but not ROM
14.	Hidalgo, 2012		✓✓			✓✓		✓✓ F, Rot		✓✓
15.	Hildago, 2013								✓✓ sitting	✓✓
16.	Hultman, 1992	✓✓	✓✓	✓✓						✓✓
17.	Kim, 2013						✓✓			✓✓
18.	Lee, 2010								✓✓ Sitting, sidelying, supine	✓✓
19.	Koumantakis, 2002								✓✓ standing	✓✓
20.	Marras, 1995		✓✓		✓✓	✓✓		✓✓ F, E, LF, Rot		✓✓
21.	McClure, 1997						✓			only study on return from F
22.	McGregor, 1995,1997		✓✓	✓✓	✓✓	✓✓		✓✓ F,E, LF, Rot		✓✓
23.	McGregor 2000		✓✓	✓✓				F,E		✓✓
24.	Mellin 1990		✓✓ (sitting)	✓✓ (4-point kneeling)	✓✓			F (sitting),E (4-point kneeling)		✓✓
25.	Newcomer, 2000A								✓✓ standing	✓✓
26.	Newcomer, 2000B								✓✓ standing	✓✓
27.	Ng, 2002	✓✓	✓✓	✓✓	✓✓	✓✓				✓✓
28.	Norton, 2004	✓✓								✓✓
29.	Nourbakhsh, 2001	✓✓								✓✓
30.	O'Sullivan, 2003								✓✓ sitting	✓✓
31.	O'Sullivan, 2013								✓✓ sitting	✓✓
32.	Paquet, 1994		✓				✓	✓✓ F		✓✓ ✓measured from T8 (all others measured from T12)
33.	Pope, 1985		✓	✓	✓	✓✓				✓✓

No.	Name										
											ROM measurement units possibly not comparable
34.	Porter, 1997		✓✓					✓✓				✓✓
35.	Sheeran, 2012									✓✓ standing, sitting		✓✓
36.	Sung, 2012					✓✓						✓✓
37.	Taimela, 1999									✓ sitting		only study on motion detection
38.	Tsai, 2010		✓✓	✓✓	✓✓	✓✓				✓✓ standing		✓✓
39.	Waddell, 1992	✓✓	✓✓	✓✓	✓✓							✓✓
40.	Willigenburg, 2012									✓ kneelsitting		only study on motion control precision
41.	Willigenburg, 2013									✓ kneelsitting		only study on motion tracking precision
42.	Wong, 2004		✓✓	✓✓	✓✓	✓✓		✓✓	✓✓ F, E, LF , Rot			✓✓
43.	Youdas, 1996, 2000	✓✓	✓✓ (sitting)	✓✓ (prone)			✓					✓✓

293

9.8. Appendix H: Characteristics of included studies for Laird et al (2014)

All studies listed alphabetically

Study (1st author), Date	n, sex, age	BMI or Weight (kg)	Sample source (and NoLBP definition)	Back pain definition • Duration • Type: (symptom pattern, diagnosis, +/- leg pain), • Pain/Activity limitation:	Back pain at time of testing? (yes/no)	Level of pain Low=0-20% Med=21-50% High=>50%	Measurement device and region measured	Movement kinematics measured	Movement method & instructions
Aluko, 2011	10 NoLBP 10 LBP Male (M) & Female (F) 21-51 years	*NoLBP: 71±14 kg* *LBP: 74±21*	*NoLBP:* University staff *No LBP for previous 6 months* *LBP:* Local hospital patients	*Duration:* 5.7±1 weeks *Type:* non-specific LBP *Pain/Activity limitation::* VAS 29±23% RMDQ 32±27%	**Yes**	Medium	Lumbar Motion monitor *Region:* T12-S2	Flexion, extension speed from neutral standing, (velocity: m/sec)	"as many flexion/extension repetitions as possible in 8 seconds"
Barrett 1999	31 NoLBP (M:14, F:17) 20-34 years LBP (M:13, F:10) 19-33 years	✕	*NoLBP:* subjects recruited from local advertising *No LBP for previous 6 months & no history of surgery* *LBP:* sourced from private physiotherapy practices	*Duration:* unknown *Type:* +/- leg pain + stiffness on movement assessment, excluded subjects with BMI> 30 *Pain/Activity limitation:* not stated	**Yes**	not stated	Electro-goniometer (3Space Fastrak, Polhemus) *Region:* L3-S1	Lateral flexion in neutral, flexion and extension (°)	Neutral standing, flexion to pain onset (or pain increase if pain in neutral standing) 3 repetitions, flexion with lateral flexion added at end range flexion (left then right),similarly for extension + lateral flexion (1 repetition)
Boline, 1992	25 NoLBP (M:8, F:17) 25 LBP (M:14, F:11) 28-38 years	✕	*NoLBP:* University staff and students *No "recent LBP lasting >2 weeks", no history of surgery* *LBP:* patients from outpatient clinic of University	*Duration:* back pain > 6 months *Type:* not stated *Pain/Activity limitation:* not stated	**Yes**	not stated	Inclinometer *Region:* T12/L1-pelvis	Rotation in 90° flexion (°)	"Brief warm up period" One repetition
Brumagne 2000	21 NoLBP (M:6, F:15) 22.3±3.8 23 LBP (M:7, F:16) 21.8±2.1	*NoLBP: 63.2±7 kg* *LBP: 64.9±7.2*	*NoLBP:* University students or staff *no definition for NoLBP* *LBP:* Hospital outpatient departments	*Duration:* not stated *Type:* not stated *Pain/Activity limitation:* VAS 38±17% ODI 14±13.6%	**Yes**	low	Electro-goniometer (accelero-meter) *Region:* S2	Pelvic tilt re-position error in *sitting* (constant, variable and absolute error)	Measured sacral (pelvic) tilt angle in sitting, ROM of pelvic tilt. Criterion angle determined, held 5 seconds, then full anterior tilt followed by a return to perceived criterion position. Repeated 5 times.
Christie 1995	20 NoLBP 39 LBP M&F 18-46 years	*NoLBP: 22.8±2.3* *LBP:* (acute) 25.9±4.2 (chronic) 24.7±3.3	*NoLBP: no LBP for previous 12 months and never pain for > 1 month* *NoLBP & LBP:* subjects sourced from selected medical institutions & university campus	*Duration:* Two groups of LBP: Group 1 > 6 months Group 2 < 6 months *Type:* not stated *Pain/Activity limitation:* not stated	**Yes**	not stated	Photography *Region:* T12-L5 (lordosis) ASIS-PSIS (pelvic tilt angle)	Lordosis in standing, sitting (°) Pelvic tilt in standing – neutral position (° angle from horizontal)	Instructions only described for postural assessment: Relaxed standing Standardised sitting instruction

Study (1st author), Date	n, sex, age	BMI or *Weight* (kg)	Sample source *(and NoLBP definition)*	Back pain definition • Duration • Type: (symptom pattern, diagnosis, +/- leg pain), • Pain/Activity limitation:	Back pain at time of testing? (yes/no)	Level of pain Low=0-20% Med=21-50% High=>50%	Measurement device and region measured	Movement kinematics measured	Movement method & instructions
Crosbie 2013	19 NoLBP (M:6, F:13) 28.6±5.4 19 LBP (M:7, F:12) 34.0±13.3	*NoLBP:* 23.0±2.4 *CLBP:* 24.5±3.6	*NoLBP & LBP:* No detail provided	*Duration:* 72month (range 8-150month) recurrent episodes *Type:* not stated *Pain/Activity limitation::* VAS 29±23% RMDQ 21% (range 0-79%)	**Yes**	*low*	Electro-magnetic (Motion Star wireless) *Region:* T6 - L1, L1-S2 (low thoracic and lumbar regions)	Flexion, rotation, lateral flexion, (º) & in walking	"several" flexion, lateral flexion movements in standing, axial rotation in sitting
Desscareaux 2005 (and 2004)	15 NoLBP (M:9, F:6) 38.2 years 16 LBP (M:11, F:5) 41.5 years	*NoLBP:* 71.9±12.1 kg *LBP:* Group 1: 75.4±13.9 Group 2: 68.1±15.2	*NoLBP:* "local advertising" *No definition* *NoLBP & LBP:* "local advertising"	*Duration:* not stated *Type:* not stated *Pain/Activity limitation:* LBP group 1 (longer time to produce isometric force, VAS 14±8%, ODI 27.4±10.8% LBP group 2 (shorter time to produce isometric force) VAS 43±9% ODI 26±9.3%	**Yes**	*low and medium*	"biomedical device" (Loredan Biomedical) – no other detail provided	*Standing* flexion (15º, 30º, 60º), extension (15º) reposition accuracy	Neutral standing with pelvis & legs immobilised, then flexion to 15°, 30° & 60°, extension to 15°. 1 repetition performed then visual feedback training until accurate repositioning to within 10% of predetermined position. Data collected from 10 consecutive trials without feedback
Day 1984	32 NoLBP (M:32) 15 LBP (M:25) 25-55 years	✕	*NoLBP:* limited detail, *No LBP for previous 6 months & no history of surgery* *LBP:* subjects from orthopaedic clinic	*Duration:* not stated *Type:* not stated *Pain/Activity limitation:* not stated	**Yes**	not stated	Electro-mechanical (Iowa anatomical position systems) *Region:* ASIS-PSIS, T12-S2	Lordosis (depth of curve- mm) Pelvic tilt – neutral (angle from horizontal), full anterior, full posterior (º)	Supine & standing pelvic tilt, practice followed by 3 recorded repetitions
Esola, 1996	21 NoLBP (M:13, F:8) 23-37 years 20 LBP (M:14, F:6) 23-46 years	*NoLBP:* 71.9±12 kg *LBP:* 75.2±17	*NoLBP & LBP:* No detail provided	*Duration:* LBP episode within last 5 years. No pain at time of testing. Average time since last episode (episode not defined) = 12.8±16.9 months *Type:* not stated *Pain/Activity limitation:* ODI 23.6±18 (at last episode) VAS 34.2±23.8 (at last episode)	**No**	*NA*	Opto-electronic (Watsmart) 3D motion analysis system *Region:* T12-S2	Flexion of lumbar spine versus hip (º) & (velocity: m/sec)	Relaxed, standing position, 3 practice flexion movements, 3 recorded movements at self-selected velocity, 15 sec rest between movements

Study (1st author), Date	n, sex, age	BMI or *Weight* (kg)	Sample source *(and NoLBP definition)*	Back pain definition • Duration • Type: (symptom pattern, diagnosis, +/- leg pain), • Pain/Activity limitation:	Back pain at time of testing? (yes/no)	Level of pain Low=0-20% Med=21-50% High=>50%	Measurement device and region measured	Movement kinematics measured	Movement method & instructions
Field 1997	16 NoLBP (M:16) 37.9 ±7.4 years 16 LBP (M:16) 38.3 ±8 years	*NoLBP: 83±8.8 kg LBP: 87±17.4*	*NoLBP:* no detail *No definition* *LBP:* subjects from outpatient hospital clinic	*Duration:* > 4 months *Type:* no detail *Pain/Activity limitation:* no detail	**Yes**	not stated	Electro-goniometer (Orthoranger II) *Region:* trunk angle at L3	Positioning error (o)	Relaxed standing, subjects shown a diagram of 45otrunk flexion (target position), blindfolded then asked to assume target position, 4 repetitions, then 4 repetitions holding 5kg load
Georgy 2011	15 NoLBP 38.5±5.9 years 30 LBP 39.9±5.3 years	*NoLBP: 83.3±8.8 kg LBP: 83±11.9*	*NoLBP:* relatives and friends of patients, *No definition* *LBP:* subjects from outpatient hospital clinic	*Duration:* > 3 months *Type:* Non specific and "discogenic" diagnosis (combined) *Pain/Activity limitation:* ODI 30.7±7.1 VAS 64±8	yes	*high*	Isokinetic dynamometer (Biodex system3) *Region:* T1-S2	Repositioning error (absolute error) of the thoracolumbar spine (°)	Sitting, 3 practice runs of flexing from neutral sitting to 30o flexion, (target) then 3 tests with subject pressing button on achieving perceived target.
Gill 1998	20 NoLBP (M:7, F:13) 24-53 years 20 LBP (M:7, F:13) 21-74 years	✗	*NoLBP:* subjects from hospital staff, *No LBP that required time off work, no current pain* *LBP:* subjects from outpatient hospital clinic	*Duration:* > 12 months *Type:* +/– leg pain *Pain/Activity limitation:* not stated	yes	not stated	Lumbar motion monitor *Region:* T12-S1	Proprioceptive position accuracy of position/reposition at 20° flexion in ***standing*** & ***4-point kneeling***	Standing (pelvis immobilised) and 4-point kneeling with visual (computer) feedback, flexion to 20°. 10 practice repetitions in each position. Blindfolded subjects attempted to reproduce position 10 times in 30 seconds
Gomez, 1994	168 NoLBP (M:85, F:83) 120 LBP (M:110, F:10) 18-68 years	*NoLBP:* M: 76.4±10.5 kg F: 59±8 *LBP* M: 79.7±11.9 F: 70.4±13.4	*NoLBP:* subjects from administrative offices *No LBP for previous 6 months & no history of surgery* *LBP:* subjects from workers compensation and backcare programs	*Duration:* Subacute and chronic (no details) *Type:* not stated *Pain/Activity limitation:* not stated	**Yes**	not stated	Standing dynamometer (B200 Isostation) *Region:* Lumbar spine, detail not reported	Rotation & lateral flexion Standing, strapped into B200 device (symmetry: ratio)	"Standardised protocol" as per B200 manual (detail not provided) Best of 2 repetitions for maximal rotation & lateral flexion 4 repetitions for flexion & extension. Reported coefficient of variation
Hidalgo, 2012	25 NoLBP (M:10, F:15) 35 LBP (M:12, F:13) 35-65 years	*NoLBP:* 23.3±2.5 *LBP:* 25.2±3.2	*NoLBP:* volunteers *No LBP for previous 6 months & no history of surgery* *LBP:* recruited from hospital program	*Duration:* Chronic (> 3months) *Type:* No pain below knee Non-specific LBP *Pain/Activity limitation:* VAS 24±17	**Yes**	*medium*	Opto-electronic (Elite) *Region:* T12-S2	Flexion, rotation, flexion+30° rotation in seated position (°) & (velocity: m/sec)	15 repetitions (10 recorded). Begin & end each movement in neutral sitting, move at self-selected speed and move as far as possible

Study (1st author), Date	n, sex, age	BMI or *Weight* (kg)	Sample source *(and NoLBP definition)*	**Back pain definition** • Duration • Type: (symptom pattern, diagnosis, +/- leg pain), • Pain/Activity limitation:	Back pain at time of testing? (yes/no)	Level of pain Low=0-20% Med=21-50% High=>50%	Measurement device and region measured	Movement kinematics measured	Movement method & instructions
Hidalgo 2013	10 NoLBP (M:5, F:5) 30.0 ±11.7 years 10 LBP (M:5, F:5) 33.8±7.5 years	**NoLBP:** 22.9±2.2 **LBP:** 22.4±2.9	**NoLBP:** *No details* **LBP:** recruited from hospital program	**Duration:** 11.4±4.7 months **Type:** Non-specific LBP No pain below knee **Pain/Activity limitation:** VAS 34±9	**yes**	*medium*	Opto-electronic (Elite) **Region:** T12-S2	Repositioning error (absolute error) of the lumbar spine (°)	Subjects were in a seated position with corrected spine posture then maintained curvature, moving at their own pace to target position of 30° with eyes closed. One warm-up trial pausing for 3 seconds to remember position then 10 repetitions recorded
Hultman, 1993	38 NoLBP (M:38) 50.2±3 years 21 LBP (M:21) 48.6±5.7 years	**NoLBP:** 26.3±4.3 **LBP:** 26.4±4.3	**NoLBP (group1):** Workers from industrial company, *No significant LBP ever* **LBP (group 3):** Workers & patients referred to hospital outpatient department	**Duration:** Chronic (>3 years and 3 months of work) **Type:** not stated **Pain/Activity limitation:** not stated	**Yes**	not stated	Debrunners kyphometer **Region:** T12-S2	Lordosis (angle) Flexion, extension (°)	Relaxed standing One practice movement then two recorded movements Standardised instructions
Kim 2013	16 NoLBP 23.8±2.9 years 17 LBP (flexion) 23.5±2.4 years 14 LBP (extension) 23.8±3.9 years	**NoLBP:** *61.3±9.2 kg* **LBP flexgrp:** *67.2±11.9* **LBP ext grp:** *65±11.2*	**NoLBP:** source not stated, *No definition provided* **LBP:** source not stated	**Duration:** not stated **Type:** LBP with no radiating pain **Pain/Activity limitation:** not stated	**?**	not stated	Opto-electronic (Vicon) motion analysis system **Region:** T12-S2	Flexion and return (standing) of lumbar spine and hip joint (°) Flexion relaxation response	Flexion from standing position, holding fully flexed position for 3 seconds. 3 trials recorded
Koumantakis 2002	18 NoLBP (M:8, F:10) 24.6±4 years 62 LBP (M:30, F:32) 38.2±10.7 years	**NoLBP:** 24±2.8 **LBP:** 26.4±3.7	**NoLBP:** source not stated, *No previous LBP history* **LBP:** source not stated	**Duration:** recurrent LBP (at least 2 episodes in last year) or > 6 weeks after acute onset **Type:** mechanical non-specific LBP **Pain/Activity limitation:** VAS 34.7±23.7% RMDQ 42±35%	**Yes**	*medium*	Triaxial electro-goniometer (Lumbar Motion monitor) **Region:** thoraco-lumbar spine (T12 to S2)	Repositioning error (absolute & variable error) of the lumbar spine (°) For: 20° flexion 15° rotation 15° lateral flexion	Standing unrestrained, practice of the 5 test positions (no of practice reps not recorded), then 3 repetitions to each of the 5 targets at subjects preferred speed NB thighs touched couch to limit lower limb contribution to rotation

Study (1st author), Date	n, sex, age	BMI or *Weight* (kg)	Sample source *(and NoLBP definition)*	Back pain definition • Duration • Type: (symptom pattern, diagnosis, +/- leg pain), • Pain/Activity limitation:	Back pain at time of testing? (yes/no)	Level of pain Low=0-20% Med=21-50% High=>50%	Measurement device and region measured	Movement kinematics measured	Movement method & instructions
Lee 2010	24 NoLBP (M:14, F:10) 42.4±9.0 years 24 LBP (M:11, F:13) 42.6±13.7 years	*NoLBP:* 73±14.8 kg *LBP:* 71.3±12.8	*NoLBP:* source not stated, *No definition provided* *LBP:* source not stated	*Duration:* > 3 months *Type:* No definition provided *Pain/Activity limitation:* ODI 19±15% VAS 40±26%	**yes**	*low*	Specifically made device *Region:* Thoracolumbar (not clearly stated)	Repositioning error (absolute error) of the lumbar spine (°) Motion perception threshold (°)	Seated, (axial rotation), side-lying (Flexion/extension) and supine (lateral flexion) test positions. Repositioning occurred with upper body fixed, lower trunk moving from 15o away from neutral. Subjects pressed a button when neutral position was re-achieved. 2 practice trials and 4 test trials for each test
Marras, 1995	339 NoLBP (M:193, F:146) 171LBP (M:96, F:75)	×	*NoLBP:* source not stated, *No LBP ever* *LBP:* subjects from secondary & tertiary referral sources	*Duration:* > 7 weeks *Type:* LBP+proximal radiation (n=16), LBP+distal radiation (n=17), LBP only (n=17), Listhesis (n=16), disc prolapse, pain<3 (n=12), disc prolapse, pain>3 (n=30), stenosis (n=11), nonorganic (n=17), scoliosis (n=9) *Pain/Activity limitation:* not stated	**Yes**	*mixed (did compare low pain to moderate + high pain subgroups for herniated disc category)*	Triaxial electro-goniometer (Lumbar Motion monitor) *Region:* "primarily the lumbar spine" no other detail provided	Flexion, extension in 0°, 15°, 30° of axial rotation, lateral flexion, rotation (°) & (velocity: m/sec) & (acceleration: m/sec^2)	Free neutral standing, one warm up practice movement followed by 4 recorded (averaged) repetitions, standardised instruction
McClure (and Esola), 1997	12 NoLBP 23-35 years 12 LBP 23-46 years	*NoLBP:* 69.5±11 kg *LBP:* 78.9±15.7	*NoLBP & LBP:* No detail provided	*Duration:* LBP episode within last 5 years. No pain at time of testing. Average time since last episode (episode not defined) = 12.8±16.9 months *Type:* not stated *Pain/Activity limitation:* ODI 25.7±6.9 (for last episode) VAS 30.8±8.2	**No**	*NA*	Opto-electronic (Watsmart) 3D motion analysis system *Region:* T12-S2	Extension (on return from full flexion) of lumbar spine versus hip (°) & (velocity: m/sec)	3 practice flexion movements, 3 movements recorded at self-selected velocity, 15 sec rest between movements
McGregor, 1995,1997	203 NoLBP (M:103, F:100) 138 LBP (M:76, F:62)	×	*NoLBP:* source not stated, *No LBP for previous 6 months* *LBP:* subjects from hospital outpatient clinic	*Duration:* not stated *Type:* Non-specific LBP (n=25), disc prolapse (n=33), degen disc disease (n=57), spondylolisthesis (n=12), stenosis (n=11) *Pain/Activity limitation:* VAS 51±28	**Yes**	*high*	CA-6000 (3D potentiometer) *Region:* T12-L5	Flexion, extension, rotation, lateral flexion, (°) & (velocity: m/sec)	Free neutral standing, one warm up practice movement 3 repetitions averaged

Study (1st author), Date	n, sex, age	BMI or *Weight* (kg)	Sample source *(and NoLBP definition)*	Back pain definition • Duration • Type: (symptom pattern, diagnosis, +/- leg pain), • Pain/Activity limitation:	Back pain at time of testing? (yes/no)	Level of pain Low=0-20% Med=21-50% High=>50%	Measurement device and region measured	Movement kinematics measured	Movement method & instructions
McGregor, 2000	15 NoLBP 33.5 ± 6.3 years, 15 LBP 58±16.4 years	✗	**NoLBP:** staff of medical teaching college, *"No current or recent history of LBP"* **LBP:** hospital spinal clinic	**Duration:** not stated **Type:** lumbar canal stenosis **Pain/Activity limitation:** not stated	**Yes**	not stated	CA-6000 (3D potentiometer) **Region:** T12-L5	Flexion, extension, (º) & (velocity: m/sec)	Free neutral standing, one warm up practice movement. 3 repetitions averaged, repeated at 3 speeds: slow, preferred, fast
Mellin 1990	48 NoLBP (M:29, F:19) 55 LBP (M:26, F:29) 21.4±1.6 years	✗	**NoLBP & LBP:** Nursing and medical students, **NoLBP:** no LBP in previous year	**Duration:** not stated **Type:** not stated **Pain/Activity limitation:** not stated	**Mixed**	not stated	Inclinometer **Region:** PSIS (S2) to 20cm cranial (lumbar spine)	Flexion, extension, lateral flexion, (º)	Flexion (in sitting), extension (in 4-point kneeling), lateral flexion (in standing)
Newcomer, 2000A	20 NoLBP (M:7, F:13) 39.1±11.3 years 20 LBP (M:8, F:12) 39.3±11.4 years	✗	**NoLBP: :** subjects from advertising, *No LBP >3 months or at any time in previous year* **LBP:** subjects from advertising	**Duration:** >3 months **Type:** not stated **Pain/Activity limitation:** VAS 48±18	**Yes**	*medium*	3Space tracker (electro-magnetic) **Region:** L1 and S1	Proprioceptive position accuracy: flexion, extension, lateral flexion & rotation in standing (reposition error º)	Relaxed neutral standing (pelvis free). Slow movement (5 seconds) flexion, extension & lateral flexion to 50% of maximum ROM. 3 repeated measures of return to 50% position were recorded. Performed with eyes open then repeated with eyes closed
Newcomer, 2000B	20 NoLBP (M:9, F:11) 39.8±12.7 years 20 LBP (M:9, F:11) 44.2±10.6 years	✗	**NoLBP:** subjects from outpatient hospital clinic & advertising, *No LBP > 3months or at any time in previous year* **LBP:** subjects from outpatient hospital clinic & advertising	**Duration:** > 6 months **Type:** not stated **Pain/Activity limitation:** VAS 29±25	**yes**	*medium*	3Space tracker (electro-magnetic) **Region:** T1 and S1	Proprioceptive position accuracy: flexion, extension & lateral flexion (reposition error º)	Standing with pelvis restrained. Slow movement (5 seconds) flexion, extension & lateral flexion to 30, 60 & 90% of maximum ROM. One repeated measure of return to each position recorded
Ng, 2002	15NoLBP 15LBP M 20-37years	**NoLBP:** 22.7±2.0 **LBP:** 23.4±1.9	**NoLBP:** source not stated, *"Without any history of back pain"* **LBP:** source not stated	**Duration:** >12 months duration **Type:** not stated **Pain/Activity limitation:** severe enough to previously receive treatment, episodic or sustained pain. Minimal pain at time of testing VAS 11±7% RMDQ 10±8.3%	**Yes**	*low*	Inclinometer (Flexion, extension, lateral flexion Rotameter (rotation) **Region:** T12-S1	Lordosis (º) Flexion, extension, lateral flexion, rotation (º)	Warm-up procedure (1 repetition of each movement) Pelvis restrained by device to eliminate pelvic/hip movement, 1 movement in each direction recorded

Study (1st author), Date	n, sex, age	BMI or *Weight* (kg)	Sample source *(and NoLBP definition)*	Back pain definition • Duration • Type: (symptom pattern, diagnosis, +/- leg pain), • Pain/Activity limitation:	Back pain at time of testing? (yes/no)	Level of pain Low=0-20% Med=21-50% High=>50%	Measurement device and region measured	Movement kinematics measured	Movement method & instructions
Norton 2004	60 NoLBP 128 LBP 19-73 years (M:85, F:103)	✗	*NoLBP:* friends, families of LBP subjects, local advertisement, *No LBP previous 12 months* *LBP:* from local physiotherapy clinics	*Duration:* not stated *Type:* LBP +/- leg pain *Pain/Activity limitation:* not stated	**Yes**	not stated	Metrocomm Skeletal Analysis System (3D) *Region:* T12-S2	Lordosis (°)	Maintain comfortable standing (lordosis) Probe traced between points, repeated 3 times
Nourbakhsh 2001	420 NoLBP (M:210, F:210) 420 LBP (M:210, F:210) 20-65years	*NoLBP:* M:*73.9±10.8kg* F:*63.9±10.4* *LBP:* M:*72.7±10.1* F:*67.2±11.1*	*NoLBP: No LBP previous 12 months, no spinal surgery* *NoLBP & LBP:* 8 metropolitan hospitals in Tehran	*Duration:* ≥ 6/52 low back pain (LBP) OR ≥ 3 episodes of LBP in previous year *Type:* not stated *Pain/Activity limitation:* not stated	**Mixed**	not stated	Flexible ruler *Region:* T12-S2	Lordosis (°)	Measured with flexible ruler using method of Youdas 1996
O'Sullivan P 2003	15 NoLBP (M:6, F:9) 38.2±10.9 years 15 LBP (M:6, F:9) 38.8±12 years	*NoLBP:* *71.6±11.8 kg* *LBP:* *73.9±18.4*	*NoLBP:* Recruited from local community, no LBP for *24 months* *LBP:* recruited from private physiotherapy clinics	*Duration:* ≥ 3 months pain with *Type:* "clinical lumbar segmental instability" flexion pattern *Pain/Activity limitation:* ODI 26.1±13.3 %	**Yes**	*medium*	3Space Fastrak (electro-magnetic) *Region:* T12, L2, L4, S2 sensors	Repositioning error (absolute error) of the lumbar spine (°)	Sitting, with 3 repetitions of flexion to extension, then positioned in neutral position for 5 seconds. Subjects then relaxed into full flexion for 5 seconds then return to previous neutral position, x 5
O'sullivan K 2013	15 NoLBP (M:10, F:5) 32.1±9.2 years 15 LBP (M:10, F:5) 31.3±10.3 years	*NoLBP:* 23.8±2.0 *LBP:* 24.3±3.2	*NoLBP:* Recruited from local community, no LBP for *24 months* *LBP:* recruited from private physiotherapy clinics	*Duration:* ≥ 3 months pain with *Type:* "clinical lumbar segmental instability" flexion pattern *Pain/Activity limitation:* VAS 33±19% ODI 14.1±7.8 %	**Yes**	*medium*	Wireless posture monitor, strain gauge (BodyGuard) *Region:* L3-S2	Repositioning error (absolute error) of the lumbar spine (°) Constant error and variable error	Sitting, then established full posterior tilt (flexion) to full anterior tilt (extension), then positioned in neutral position for 5 seconds. Subjects then relaxed into full flexion for 5 seconds then return to previous neutral position. 1 practice then 3 recorded trials
Paquet 1994	10 NoLBP 34±10 years 10 LBP 38±14 years	*NoLBP:* *79±12 kg* *LBP:* *81±14*	*NoLBP:* Laboratory workers, *No detail provided* *LBP:* Medical clinic outpatients	*Duration:* 7days to 7 weeks, *Type:* no leg pain *Pain/Activity limitation:* VAS 32±13	**Yes**	*medium*	Electro-goniometer (self-developed) *Region:* T8-S1	Flexion of lumbar spine & hip (°) & (velocity: m/sec)	Comfortable standing, 5 flexion & return movements recorded at self-selected velocity, 5 flexion & return at specific velocity

Study (1st author), Date	n, sex, age	BMI or *Weight* (kg)	Sample source *(and NoLBP definition)*	Back pain definition • Duration • Type: (symptom pattern, diagnosis, +/- leg pain), • Pain/Activity limitation:	Back pain at time of testing? (yes/no)	Level of pain Low=0-20% Med=21-50% High=>50%	Measurement device and region measured	Movement kinematics measured	Movement method & instructions
Pope, 1985 (and Frymoyer, 1983)	106 NoLBP 225 LBP (144 moderate LBP, 71 severe LBP) M 18-55 years	*NoLBP: 78±11.3 kg* Moderate *LBP: 79.8±12.4* Severe LBP *81.1±13.7*	*NoLBP & LBP:* subjects sourced from large medical practice *No detail provided*	*Duration:* not stated *Type:* not stated *Pain/Activity limitation:* categorised as moderate or severe (no other detail provided)	**Yes**	*"moderate" and "severe"*	Potentiometer *Region:* T9 – S1	Flexion, extension, lateral flexion, rotation (º)	Harness positioned at T9, attached to potentiometer, fixed pelvis . No other detail provided
Porter, 1997	17 NoLBP 15 LBP M 18-36 years	✗	*NoLBP & LBP:* No detail provided	*Duration:* Chronic LBP defined as episode of LBP. 49 days in previous 12months + current pain, +/- leg pain *Type:* not stated *Pain/Activity limitation:* categorised as moderate or severe (no other detail provided)	**Yes**	not stated	3Space tracker (Polhemus) *Region:* T12-S2	Flexion, lumbar spine & hip (º) (hip versus lumbar contribution to trunk flexion, at 15º, 30º, 60º, 90º, & 120º)	Flexion with extended knees from relaxed standing and return to standing, 2 practice movements, 1 recorded movement
Sheeran 2012	35 NoLBP (M:13, F:22) 36±10.3 y 90 LBP (M:21, F:59) 34.5±10.8 years	*NoLBP:* 23.3±2.2 *LBP:* 25.1±3.3	*NoLBP:* no detail provided *LBP:* sourced from people referred for physiotherapy to hospital board Divided into flexion pattern (n=51) and active extension group (n=39)	*Duration:* >3 months, *Type:* pain in lumbar or buttock region, clear mechanical basis with aggravating & easing movement directions, pattern of flexion or extension *Pain/Activity limitation:* Flexion group: RMDQ 30±16 %, current pain 48±13% (Active) Extension group: RMDQ 26±15 %, current pain 45±14%	**Yes**	*medium*	Opto-electronic (Vicon) and computer-assisted, mechanical (Spinal Mouse) *Region:* L1-L5 *(and T1-T12)*	Flexion, extension re-positioning error Absolute error (magnitude), variable error (consistency) & constant error (direction) (º)	Subjects seated, blindfolded, performed 3 flexion & extension movements, then placed in a mid-range, neutral position for 5 seconds to be memorised. Subjects relaxed in usual sitting 5 seconds then attempted to reproduce memorised position 4 times. Process repeated in standing.
Sung, 2012	15NoLBP 41.8±16.88 15LBP 47.9±13.8 years (M:14&F:16)	*NoLBP: 70.5±8. kg* *LBP:* 64.8±10.5	*NoLBP & LBP:* No detail provided	*Duration:* > 2 months *Type:* no leg pain *Pain/Activity limitation:* ODI 20±48% (range 0-37%)	**Yes**	not stated	Motion analysis labortatory, reflective markers *Region:* T12-S2 (and thoracic spine measured separately)	Axial rotation of upper thorax, lower thorax and lumbar regions (º)	Standing upright, holding bar at shoulder height then rotating body, knees extended, feet fixed, 5 repetitions

Study (1st author), Date	n, sex, age	BMI or Weight (kg)	Sample source (and NoLBP definition)	Back pain definition • Duration • Type: (symptom pattern, diagnosis, +/- leg pain), • Pain/Activity limitation:	Back pain at time of testing? (yes/no)	Level of pain Low=0-20% Med=21-50% High=>50%	Measurement device and region measured	Movement kinematics measured	Movement method & instructions
Taimela, 1999	49 NoLBP (M:28, F:21) 38±9 y 57 LBP (M:27, F:30) 41±7 years	*NoLBP:* M:80.9±9.2 kg, F:64±7.2 *LBP:* M:82.6±14 F:64.5±8.9	*NoLBP & LBP:* sourced via advertisement in local newspapers *No significant LBP requiring medical attention in previous 2 years*	*Duration:* >3 months *Type:* non-specific LBP *Pain/Activity limitation:* Male: VAS 52±19%, ODI 21±9%, Female: VAS 61±23%, ODI 26±16%	**Yes**	*high*	Specifically manufactured rotating seat *Region:* Lumbar spine (non- specific)	Proprioception of axial rotation in lumbar spine (°) Motion perception threshold (msec)	Subjects blindfolded, seated in neutral position, holding a switch, which is pressed when movement (rotation) detected in lumbar spine. Seat rotates at 1°/sec. Standardized practice then measurement of magnitude of seat rotation recorded on 5 repetitions. Two tests, before and after fatiguing process with resisted flexion/extension exercise
Tsai 2010	16NoLBP 47.9±8.3 16LBP 48.6±7.4 years (M:14&F:16)	*NoLBP:* 87.5±9.6 kg *LBP:* 88.3±18.2	*NoLBP:* No detail provided *LBP:*	*Duration:* one episode within last 2 years with ODI>24% & required conservative treatment *Type:* "mechanical LBP" *Pain/Activity limitation:* VAS 0 ODI 45.3±18.2% (at time of episode)	**No**	*NA*	Opto-electronic (Vicon) *Region:* T1 – S1	Flexion, extension, lateral flexion , rotation (°), Flexion, extensión, lateral flexion & rotation (left & right) re-positioning error (absolute) (°)	Subjects stood with pelvis immobilised, one repetition of full ROM in each direction (recorded for ROM comparison), blindfolded, moved to 8-% maximum ROM for 4 seconds, returned to neutral then asked to move back to target x6 for each direction
Waddell, 1992	70NoLBP 120LBP M&F 20-55	✗	*NoLBP:* from hospital patients with hand injuries, hospital visitors and staff, *no current pain nor history of LBP requiring medical attention of time off work in previous months* *LBP:* subjects from orthopaedic outpatient clinic	*Duration:* > 3 months *Type:* +/- thigh pain but no radiculopathy signs *Pain/Activity limitation:* collected but not reported	**Yes**	not stated	Electric inclinometer (Cybex / Lumex) *Region:* T12-S1	Flexion, extension, lateral flexion (°)	Flexion, Extension, Rotation, Lateral flexion x2 as warm-up. Third repetition recorded. Standardised position and instruction.

Study (1st author), Date	n, sex, age	BMI or Weight (kg)	Sample source (and NoLBP definition)	Back pain definition • Duration • Type: (symptom pattern, diagnosis, +/- leg pain), • Pain/Activity limitation:	Back pain at time of testing? (yes/no)	Level of pain Low=0-20% Med=21-50% High=>50%	Measurement device and region measured	Movement kinematics measured	Movement method & instructions
Willigenburg 2012	13 NoLBP (M:9, F:4) 34.3±11.9 y 20 LBP (M:11, F:9) 33.4±15.5 years	NoLBP: 22.9±2.4 LBP: 23.6±3	NoLBP & LBP: No detail provided	Duration: > 6 weeks Type: non specific LBP Pain/Activity limitation: VAS 27±19%	Yes	medium	Opto-electronic (OptoTrak) Region: T12 and pelvic marker	Deviation from neutral position - % time on target - Accuracy (average ° change from initial angle) - Precision (used SDs) -	Kneel sitting position, adopting a "neutral" posture while watching realtime visual biofeedback with a black dot representing actual position. Subjects had to keep the dot contained within a small square (0.2o range) representing high precision trunk control then then large square (2.7o range) for 30 seconds representing low precision control
Willigenburg 2013	13 NoLBP (M:9, F:4) 34.3±11.9 y 18 LBP (M:11, F:9) 31±14 years	NoLBP: 22.9±2.4 LBP: 23.4±2.4	NoLBP & LBP: No detail provided	Duration: > 6 weeks Type: non specific LBP Pain/Activity limitation: ODI 15.2±4.2 VAS 27±19%	Yes	medium	Opto-electronic (OptoTrak) Region: T12 and pelvic marker	Tracking error (absolute difference between trunk angle and target angle)	Kneel sitting position, adopting a "neutral" posture while watching realtime visual biofeedback with a black dot representing actual position. Subjects were asked to keep black dot located within a yellow rectangle which was programmed to move in a spiral trajectory of 5 circles. Task took 2 minutes. 2 trials starting at centre of spiral moving outwards and 2 at end of spiral moving inwards. Angles in sagittal & frontal planes calculated
Wong, 2004	20 NoLBP 42±8 y 24LBP (group 2) 41±11 years 21 LBP+ive SLR (group 3) 34±10 years	NoLBP: 71.4±10.5 kg LBP: Group 2 68.6±5.5 Group 3: 71.4±4.5.	NoLBP & LBP: sourced from university & outpatient physiotherapy clinic No significant LBP or leg pain in previous year	Duration: not stated Type: back pain only or back + positive straight leg raise Pain/Activity limitation: Group 2 RMDQ: 42±16, VAS 60±20%, Group 3 RMDQ: 50±16, VAS 60±20%	Yes	high	3Space Fastrak (electro-magnetic) Region: L1 and S2, bilateral hips	Flexion, extension (Lx & hip), lateral flexion and rotation (Lx only) (°), velocity (deg/sec)	Warm-up flexion, extension, lateral flexion & rotation in comfortable standing. 3 repetitions recorded at self-selected pace

Study (1st author), Date	n, sex, age	BMI or *Weight* (kg)	Sample source *(and NoLBP definition)*	Back pain definition • Duration • Type: (symptom pattern, diagnosis, +/- leg pain), • Pain/Activity limitation:	Back pain at time of testing? (yes/no)	Level of pain Low=0-20% Med=21-50% High=>50%	Measurement device and region measured	Movement kinematics measured	Movement method & instructions
Youdas 1996, 2000	90 NoLBP (M:45, F:45) 40-70 years 60 LBP (M:30, F:30) 40-70 years	*NoLBP:* M:26.6±3.5 F: 26.1±5 *LBP:* M:26.9±3.6 F:28.9±5.7	*NoLBP:* personal contact, personnel from Mayo clinic, ad in newspaper *No current LBP, no surgery, no history of hospitalisation for LBP* *LBP:* subjects sourced from local advertisement at institute, newspaper	*Duration:* > 4 months *Type:* not stated *Pain/Activity limitation:* ODI M: 15±9.5, F:26.7±9.7	**Yes**	not stated	Inclinometer (pelvic tilt) Flexible rule for all other measurements *Region:* T12-S2	Pelvic inclination (angle from vertical), lumbar lordosis, flexion, extension (°)	Comfortable standing (pelvic tilt, lordosis) Sitting, instructed to "place head between knees" x 3 as preparation then 1 recorded repetition (flexion) Prone, press up with hips on couch 1 repetition (extension)

NOLBP no low back pain; LBP low back pain; NSLBP non-specific low back pain; F flexion; E extension; LF lateral flexion; rot rotation; VAS 100 point visual analogue scale for pain intensity; RMDQ = Roland Morris Disability Questionnaire for activity limitation (converted to %); ✗ not reported

Quality assessment results

	Study (1st author, date)	Selection bias						Measurement and outcome bias								Between-group statistical comparisons are reported for at least one key outcome	Total Score
		Was the study population adequately described?	Where both groups drawn from the same population (or age/sex matched)?	Were both groups comparable for age, sex, BMI/weight	Was pain intensity and/or activity limitation described for LBP group?	Were characteristics of those with back pain described?	Score for selection bias (Maximum score = 5)	Description enables accurate replication of the measurement procedures	Instrument used to measure described	A system for standardising movement instructions is reported	Were assessors trained in standardised measurement procedure?	Did the same assessors test those with and without back pain?	Were assessors blinded as to which group subjects were in?	Was the same assessment procedure applied to those with and without back pain?	Score for measurement and outcome bias (maximum score = 7)		
1.	Aluko 2011	Y	n	Y	Y	Y	4	Y	Y	n	n	n	n	Y	3	n	7
2.	Barrett 1999	n	n	Y	n	n	1	Y	Y	n	n	n	n	Y	3	Y	4
3.	Boline 1992	Y	Y	n	n	n	2	Y	Y	n	Y	Y	n	n	4	n	6
4.	Brumagne 2000	Y	n	Y	Y	n	3	Y	Y	n	n	n	n	Y	3	Y	6
5.	Christie 1995	n	n	n	n	Y	1	Y	Y	Y	n	n	n	Y	4	Y	5
6.	Crosbie 2013	Y	n	Y	Y	n	3	n	Y	n	n	n	n	Y	2	Y	5
7.	Day 1984	n	n	n	n	n	0	Y	Y	Y	n	Y	n	Y	5	Y	5
8.	Descarreaux 2005	Y	Y	Y	Y	n	4	n	n	n	n	n	n	Y	1	Y	5
9.	Esola 1996	Y	n	Y	Y	n	3	Y	Y	Y	n	n	n	Y	4	Y	7
10.	Field 1997	n	Y	n	n	n	1	Y	Y	n	n	Y	n	Y	4	Y	5

#	Study (1st author, date)	Was the study population adequately described?	Where both groups drawn from the same population (or age/sex matched)?	Were both groups comparable for age, sex, BMI/weight	Was pain intensity and/or activity limitation described for LBP group?	Were characteristics of those with back pain described?	Score for selection bias (Maximum score = 5)	Description enables accurate replication of the measurement procedures	Instrument used to measure described	A system for standardising movement instructions is reported	Were assessors trained in standardised measurement procedure?	Did the same assessors test those with and without back pain?	Were assessors blinded as to which group subjects were in?	Was the same assessment procedure applied to those with and without back pain?	Score for measurement and outcome bias (maximum score = 7)	Between-group statistical comparisons are reported for at least one key outcome	Total Score
11.	Georgy 2011	n	Y	n	Y	n	2	Y	Y	n	n	n	n	Y	5	Y	7
12.	Gill 1998	n	n	n	n	n	0	Y	Y	Y	n	Y	n	Y	5	Y	5
13.	Gomez 1994	Y	n	n	n	n	1	n	Y	Y	n	n	n	Y	4	Y	5
14.	Hidalgo 2012	Y	n	Y	n	Y	3	Y	Y	n	n	n	n	Y	3	Y	6
15.	Hidalgo 2013	Y	n	Y	Y	N	3	Y	Y	n	n	n	n	Y	3	Y	6
16.	Hultman 1993	Y	Y	Y	n	N	3	Y	Y	Y	n	Y	n	Y	5	Y	8
17.	Kim 2013	n	n	n	n	Y	1	Y	Y	n	n	n	n	n	2	Y	3
18.	Koumantakis 2002	n	n	n	Y	N	1	Y	Y	n	n	n	n	n	2	Y	3
19.	Lee 2010	Y	n	Y	Y	N	3	Y	Y	Y	n	n	n	Y	4	Y	7
20.	Marras 1995	n	n	n	n	Y	1	Y	Y	Y	n	n	n	Y	4	Y	5
21.	McClure 1997	Y	n	Y	Y	N	3	Y	Y	Y	n	n	n	Y	4	Y	7
22.	McGregor 1995,1997	n	n	n	Y	Y	2	Y	Y	n	n	n	n	Y	3	Y	5
23.	McGregor 2000	n	Y	n	n	Y	2	Y	Y	n	n	n	n	Y	3	Y	5

#	Study (1st author, date)	Was the study population adequately described?	Where both groups drawn from the same population (or age/sex matched)?	Were both groups comparable for age, sex, BMI/weight	Was pain intensity and/or activity limitation described for LBP group?	Were characteristics of those with back pain described?	Score for selection bias (Maximum score = 5)	Description enables accurate replication of the measurement procedures	Instrument used to measure described	A system for standardising movement instructions is reported	Were assessors trained in standardised measurement procedure?	Did the same assessors test those with and without back pain?	Were assessors blinded as to which group subjects were in?	Was the same assessment procedure applied to those with and without back pain?	Score for measurement and outcome bias (maximum score = 7)	Between-group statistical comparisons are reported for at least one key outcome	Total Score
		Selection bias						**Measurement and outcome bias**									
24.	Mellin 1990	n	Y	n	n	N	**1**	Y	Y	n	n	n	n	Y	**3**	Y	**4**
25.	Newcomer 2000A	n	Y	n	Y	N	**2**	Y	Y	n	n	Y	n	Y	**4**	Y	**6**
26.	Newcomer 2000B	n	Y	n	Y	N	**2**	Y	Y	n	n	Y	n	Y	**4**	Y	**6**
27.	Ng 2002	Y	n	Y	Y	N	**3**	Y	Y	Y	n	n	n	Y	**4**	Y	**7**
28.	Norton 2004	n	Y	n	n	N	**1**	Y	Y	n	Y	n	n	Y	**4**	Y	**5**
29.	Nourbakhsh 2001	Y	Y	Y	n	N	**3**	Y	Y	Y	n	n	n	Y	**4**	Y	**7**
30.	O'Sullivan P 2003	Y	Y	Y	Y	Y	**5**	Y	Y	n	n	n	n	Y	**3**	Y	**8**
31.	O'Sullivan K 2013	Y	Y	Y	Y	Y	**5**	Y	Y	n	n	n	n	Y	**3**	Y	**8**
32.	Paquet 1994	n	n	Y	Y	Y	**3**	Y	Y	n	n	n	n	Y	**3**	Y	**6**
33.	Pope 1985	Y	n	n	n	N	**1**	Y	Y	Y	n	n	n	Y	**4**	n	**5**
34.	Porter 1997	n	n	n	n	Y	**1**	Y	Y	Y	n	n	n	n	**3**	Y	**4**
35.	Sheeran 2012	Y	n	n	Y	Y	**3**	Y	Y	n	n	Y	n	Y	**4**	Y	**7**
36.	Sung 2012	Y	Y	Y	n	Y	**4**	n	n	n	n	n	n	Y	**1**	Y	**5**

	Study (1st author, date)						**Selection bias**								**Measurement and outcome bias**			
		Was the study population adequately described?	Where both groups drawn from the same population (or age/sex matched)?	Were both groups comparable for age, sex, BMI/weight	Was pain intensity and/or activity limitation described for LBP group?	Were characteristics of those with back pain described?	**Score for selection bias (Maximum score = 5)**	Description enables accurate replication of the measurement procedures	Instrument used to measure described	A system for standardising movement instructions is reported	Were assessors trained in standardised measurement procedure?	Did the same assessors test those with and without back pain?	Were assessors blinded as to which group subjects were in?	Was the same assessment procedure applied to those with and without back pain?	**Score for measurement and outcome bias (maximum score = 7)**	Between-group statistical comparisons are reported for at least one key outcome	**Total Score**
37.	Taimela 1999	Y	Y	Y	Y	N	**4**	Y	Y	Y	n	n	n	Y	**4**	Y	**8**
38.	Tsai 2010	n	Y	Y	Y	N	**3**	Y	Y	n	n	n	n	Y	**3**	Y	**6**
39.	Waddell 1992	n	Y	n	n	Y	**2**	Y	Y	Y	n	n	n	Y	**4**	Y	**6**
40.	Willigenburg 2012	n	n	Y	Y	N	**2**	Y	Y	n	n	n	n	Y	**3**	Y	**5**
41.	Willigenburg 2013	Y	n	Y	Y	N	**3**	Y	Y	n	n	n	n	Y	**3**	Y	**6**
42.	Wong 2004	n	Y	Y	Y	N	**3**	Y	Y	n	n	n	n	Y	**3**	Y	**6**
43.	Youdas 1996, 2000	Y	n	Y	Y	N	**3**	Y	Y	n	n	n	n	Y	**3**	Y	**6**
	TOTAL Score & Percentage Yes %	**23/41 (57%)**	**16/41 (39%)**	**22/41 (54%)**	**3/41 (56%)**	**14/41 (34%)**	**2.4/5 48% avg.**	**37/41 (90%)**	**39/41 (95%)**	**15/41 (37%)**	**2/41 (2%)**	**7/41 (17%)**	**0 (0%)**	**38/41 (93%)**	**3.4/7 49% avg.**	**38 (94%)**	**5.8/12 48% avg.**

9.10. Appendix J: Summary of studies examining lumbar proprioception

	Author, Date	Position	Type of test	Region measured	Movement direction tested	Movement kinematics measured	Angle of re-positioning	Number of test movts before data collection
1	Brumagne 2000	sitting	re-position	S2	Sagittal	Pelvic tilt re-position error in sitting (constant, variable and absolute error)	Neutral sitting	1
2	Descarreaux 2005	standing	re-position	"trunk"	Sagittal	Standing flexion (15°, 30°, 60°), extension (15°) reposition accuracy Temporal symmetry	15,30, 60° flexion, 15° extension	Yes, unlimited until accuracy (within 10%) was achieved
3	Georgy, 2011	sitting	re-position	T1-S2	Sagittal	Repositioning error (absolute error) of the thoracolumbar spine (°)	30° flexion	3
4	Gill 1998	standing, 4 point kneeling	re-position	T12-S1	Sagittal	Proprioceptive position accuracy of position/reposition at 20° flexion in standing & 4-point kneeling		10
5	Hidalgo, 2013	sitting	re-position	T12-S2	Sagittal	Repositioning error (absolute error) of the lumbar spine (°)	30° flexion	1
6	Koumantakis 2002	Standing	re-position	T12-S2	Sagittal Transverse Frontal	Repositioning error (absolute error) of the lumbar spine (°),	flexion 20°, rotation, lateral flexion to 15°	unknown
7	Lee 2010	Sitting, sidelying, supine	re-position Motion perception threshold	Thoraco-lumbar (not clearly stated)	Sagittal Transverse Frontal	Repositioning error (absolute error) of the lumbar spine (°) Motion perception threshold (°)	15° flexion	2
8	Newcomer, 2000A	standing	re-position	L1 and S1	Sagittal Transverse Frontal	Proprioceptive position accuracy: flexion, extension, lateral flexion & rotation in standing (reposition error °)	50% max ROM	1
9	Newcomer, 2000B	standing	re-position	T1 and S1	Sagittal Transverse Frontal	Proprioceptive position accuracy: flexion, extension & lateral flexion (reposition error °)	30, 60, 90% max ROM	1

10	O'Sullivan,P 2003	sitting	re-position	T12, L2, L4, S2 sensors	Sagittal	Repositioning error (absolute error) of the lumbar spine (^{o})	Neutral sitting	1
11	O'Sullivan,K 2013	sitting	re-position	L3-S2	Sagittal	Repositioning error (absolute error) of the lumbar spine (^{o}) Constant error and variable error	Neutral sitting	1
12	Sheeran, 2012	standing, sitting	re-position	L1-L5 and T1-T12	Sagittal	Flexion, extension re-positioning error Absolute error (magnitude), variable error (consistency) & constant error (direction) (^{o})	Neutral	1
13	Taimela, 1999	sitting	Motion perception threshold	Lumbar spine (non-specific)	Transverse	Propioception of axial rotation in lumbar spine (^{o}) Motion perception threshold (msec)	NA	Not stated
14	Willigenburg 2012	Kneel-sitting	Motion control precision	T12 and pelvic marker		Deviation from neutral position - % time on target - Accuracy (average ^{o} change from initial angle) - Precision (used SDs)	NA	1
15	Willigenburg2013	Kneel-sitting	Motion tracking precision	T12 and pelvic marker		Tracking error (absolute difference between trunk angle and target angle)	NA	1

9.11. Appendix K: Laird et al. (2016) PDF version

RESEARCH ARTICLE

CrossMark

How consistent are lordosis, range of movement and lumbo-pelvic rhythm in people with and without back pain?

Robert A. Laird[1,4*], Peter Kent[2,3] and Jennifer L. Keating[1]

Abstract

Background: Comparing movements/postures in people with and without lower back pain (LBP) may assist identifying LBP-specific dysfunction and its relationship to pain or activity limitation. This study compared the consistency in lumbo-pelvic posture and movement (range and pattern) in people with and without chronic LBP (>12 week's duration).

Methods: Wireless, wearable, inertial measurement units measured lumbar lordosis angle, range of movement (ROM) and lumbo-pelvic rhythm in adults ($n = 63$). Measurements were taken on three separate occasions: two tests on the same day with different raters and a third (intra-rater) test one to two weeks later. Participants performed five repetitions of tested postures or movements. Test data were captured automatically. Minimal detectable change scores (MDC_{90}) provided estimates of between-test consistency.

Results: There was no significant difference between participants with and without LBP for lordosis angle. There were significant differences for pelvic flexion ROM (LBP 60.8°, NoLBP 54.8°, $F_{(1,63)} = 4.31$, $p = 0.04$), lumbar right lateral flexion ROM (LBP 22.2°, NoLBP 24.6° $F_{(1,63)} = 4.48$, $p = .04$), trunk right lateral flexion ROM (LBP 28.4°, NoLBP 31.7°, $F_{(1,63)} = 5.9$, $p = .02$) and lumbar contribution to lumbo-pelvic rhythm in the LBP group (LBP 45.8 %, $F_{(1,63)} = 4.20$, NoLBP 51.3 % $p = .044$). MDC_{90} estimates for intra and inter-rater comparisons were 10°–15° for lumbar lordosis, and 5°–15° for most ROM. For lumbo-pelvic rhythm, we found 8–15 % variation in lumbar contribution to flexion and lateral flexion and 36–56 % variation in extension. Good to excellent agreement (reliability) was seen between raters (mean $r = .88$, ICC (2,2)).

Conclusion: Comparisons of ROM between people with and without LBP showed few differences between groups, with reduced relative lumbar contribution to trunk flexion. There was no difference between groups for lordosis. Wide, within-group differences were seen for both groups for ROM and lordosis. Due to variability between test occasions, changes would need to exceed 10°–15° for lumbar lordosis, 5°–15° for ROM components, and 8–15 % of lumbar contribution to lumbo-pelvic rhythm, to have 90 % confidence that movements had actually changed. Lordosis, range of movement and lumbo-pelvic rhythm typically demonstrate variability between same-day and different-day tests. This variability needs to be considered when interpreting posture and movement changes.

Keywords: Low back pain, Movement disorders, Posture, ROM, Lordosis, Lumbo-pelvic rhythm, Reliability

* Correspondence: robert.laird@monash.edu
[1]Department of Physiotherapy, Monash University, PO Box 527, Frankston, VIC 3199, Australia
[4]380 Springvale Rd, Forest Hill, 3131 Melbourne, VIC, Australia
Full list of author information is available at the end of the article

Laird *et al. BMC Musculoskeletal Disorders* (2016) 17:403

Page 2 of 14

Background

In a recent 'Global Burden of Disease Study' [1], low back pain (LBP) was rated as the health condition responsible for the most years lived with disability when all common diseases were considered. Despite considerable research efforts, it is still unclear why some people recover from LBP pain and others do not, or how to match available interventions to care-seekers [2]. Many studies have focused on movement irregularities and patterns in LBP. Movement range has been used to monitor recovery status following interventions, and various patterns of movement have been investigated, including lumbar versus pelvic (hip) contribution to trunk movement (often called lumbo-pelvic rhythm) [3–9]. Opinions vary regarding the utility of measuring movement range and patterns. Nevertheless, many non-invasive interventions continue to target movement dysfunction in people with LBP.

A concept with current support is that individuals have consistent, and therefore recognisable, patterns of posture and movement, which may contribute to ongoing LBP [10–13]. Movement patterns such as excessive end range lumbar movements or postures [14], excessive or reduced lumbar contribution to trunk flexion [15], trunk rigidity [16], loss of flexion relaxation response [17], and reduced proprioception [18, 19], amongst others, have been linked to LBP. Recent research supports the concept that individualised approaches to modification of posture and movement patterns might reduce LBP [20, 21]. However, the relationship between specific movement characteristics/ postures and LBP remains unclear. A recent systematic review of common movement characteristics in people with and without LBP concluded that people with LBP typically have reduced range of lumbar spine movement, move more slowly and have reduced proprioception compared to people without LBP [22]. Another recent review found only limited evidence for identifying and monitoring changes to movement patterns or postures [23].

Aberrant movement (range or patterns) and/or postures associated with LBP might be identifiable, provided these movements were consistent and could be accurately measured. Of particular clinical interest is the consistency of an individual's typical movement over short time periods (e.g., within a clinical session on the same day) and over longer time periods (e.g., 1 to 2 weeks apart). Common therapeutic targets of 'improving posture' and normalising dysfunctional movements are often influenced by within-session or between-session changes in movements following a treatment. Therefore, knowledge of the kinematic stability of movement patterns both within and between treatment sessions is important to clinicians who aim to identify, label and treat movement 'dysfunctions'. If movement/postural patterns normally fluctuate, and the variance in measures of

movement/posture can be quantified, measurements outside the range of expected variation are likely to represent true movement alteration/adaptation. Those adaptive movements could be used to quantify response to treatment or to identify movements that either trigger, or are a response to, LBP.

Investigating the associations between movement and pain has been limited by difficulty in measuring and monitoring typical movement/posture both within clinical settings and in normal daily activity. Technological advances with movement sensors have enabled new opportunities to investigate the relationship between movement and pain [24–26]. These devices are skin surface-mounted and generate data on lumbo-pelvic movements and postures, such as angle, timing, position and concurrent surface electromyography. There is preliminary evidence of high levels of accuracy relative to laboratory based opto-electronic measurement systems and they appear to have sufficient accuracy for clinical applications [24, 27].

This study investigated and compared consistency in lumbo-pelvic posture and movement (range and pattern) in people with and without chronic LBP (>12 week's duration). We examined the consistency (repeatability/ measurement stability) of three types of lumbo-pelvic kinematic characteristics: (i) the postural characteristic of lordosis, (ii) range of movement (ROM) of flexion, extension, and lateral flexion, and (iii) lumbar compared to pelvic contributions to movement (lumbo-pelvic rhythm). Three types of movement consistency were of interest: 1) the consistency demonstrated when an individual repeats the same movement within a single test, 2) the consistency demonstrated when a person is tested twice by two different raters on the same day, and 3) the consistency demonstrated when a person has a repeated test by the same person 7–14 days after the first test.

Methods

Study selection: inclusion and exclusion criteria

Participants (with and without LBP) were recruited by poster and word-of-mouth advertising from private physiotherapy clinics and a university. People with LBP (LBP group) were included if they had back +/− leg pain for > 12 weeks and a pain score of > 2 on a 0 to 10 Numerical Rating Scale (average of worst, current, usual pain intensity) [28]. Exclusion criteria were any of the following: (i) previous lumbar surgery, (ii) any invasive spinal procedures for LBP, including therapeutic injections, within the last 12 months, (iii) pregnancy (iv) neoplasm, infection, fracture, inflammatory disease, neurological disease or any metabolic disorder that had the potential to affect the lumbo-pelvic region, (v) implanted electrical medical device, (vi) any medical abnormalities or conditions

Laird *et al. BMC Musculoskeletal Disorders* (2016) 17:403

Page 3 of 14

(e.g., knee or hip conditions) that in the opinion of the clinician would substantively interfere with an ability to participate in the study, (vii) a known allergic skin reaction to adhesive tapes or plasters, or (viii) BMI > 30 (where it becomes difficult to palpate bony landmarks). Participants recruited into the sample without back pain (NoLBP group) were excluded if they had (i) back pain at the time of testing, (ii) an episode of back pain that had necessitated attending a medical practitioner or allied health professional in the last 12 months, (iii) time off work due to back pain in the last 12 months or, (iv) any back pain during or between testing procedures. All potential participants were screened for suitability by a trained administrator, by direct contact and follow-up phone call if clarification was required, and then invited to participate. Ethics approval was obtained from Monash University (approval numberCF12/1995-20 12001090). All participants gave written informed consent.

Measurement protocol

Figure 1 presents the test procedures. Each participant was tested on two separate days. On the first test day, they were tested twice (Test 1 and Test 2) by two different raters (Raters A and B). On the second test day, they were assessed once (Test 3) by Rater A. On each test occasion, participants were assessed while they performed five repetitions of each movement. Data were collected at two geographic locations by physiotherapists with a minimum of 2 years' clinical experience.

To standardise the testing procedures, 3 h of practice for standardised palpation of bony landmarks, sensor placement and measurement procedures preceded the initial data collection. Standardised instructions were used by both raters with pre-determined verbal cues for each movement test. Rater order (i.e., who administered Tests 1 or 2) was randomised pragmatically by rater availability. Participants were tested in the same room for all tests, and where possible, were tested at a similar time of day.

All kinematic data were automatically captured by the ViMove system independently of actions by the rater.

Equipment

The ViMove system (DorsaVi, Australia) is an inertial measurement system comprised of two wireless movement sensors containing a triaxial accelerometer, a triaxial gyroscope and a magnetometer, two wireless surface electromyography (EMG) sensors (these EMG data were not reported in this paper), and a small wireless recording device that can be easily carried (e.g., in a pocket). The manufacturer reports average differences of < 1° for single plane, through-range movements when comparing matched measurements from the ViMove and a Fastrak opto-electronic device [29]. The ViMove movement sensors collect data at approximately 20 Hz.

Test procedures

Participants were partially undressed to expose the body from T12 to the posterior superior iliac spines (PSIS) (see Fig. 2). Shoes were removed. The upper border of each PSIS was palpated and marked by Rater 1. To standardise sensor placement, the distance from the PSIS marker to the floor was recorded using a rigid vertical ruler and right-angled square. These measurements were used to replicate PSIS markings in subsequent testing [30]. A plastic template (part of the ViMove system) for standardising relative sensor placement was then aligned to the marking on the PSIS and used to guide sensor attachments. Movement sensors were attached to the skin over the T12 and S2 spinous processes using disposable adhesive pads. Movements were then demonstrated by the rater, after which participants were instructed to move through a standardised sequence of movements (summarised in Additional file 1).

During these movements, data on lumbo-pelvic angles and ROM were recorded automatically by the device. The only role of the rater was to request the required movement in the required sequence and initiate the data collection process. On completion of a test, sensors and adhesive pads were removed and the skin was wiped clean. Participants rested for 5 min then the entire procedure was immediately repeated by a second rater. Each rater was blind to data collected by the other rater
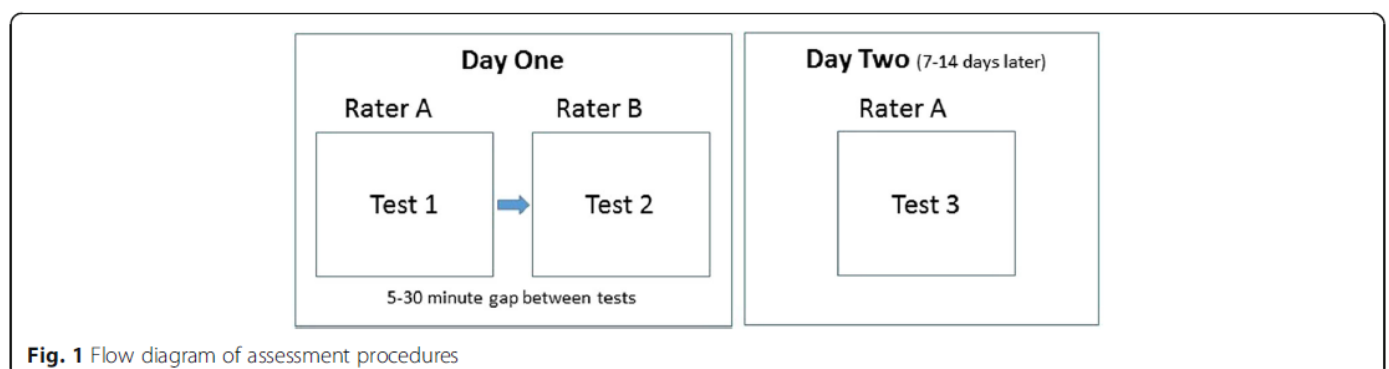

Fig. 1 Flow diagram of assessment procedures

Laird *et al. BMC Musculoskeletal Disorders* (2016) 17:403
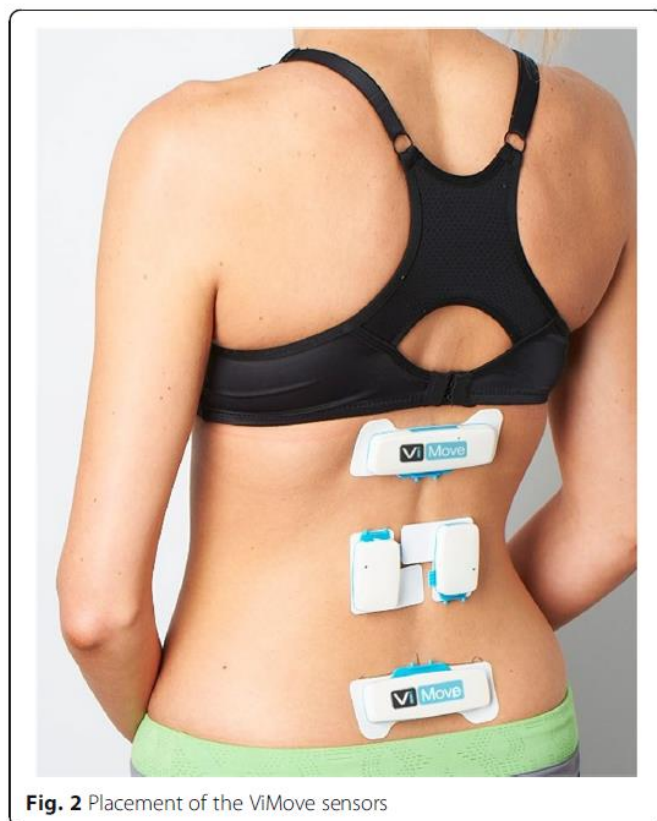
Page 4 of 14

Fig. 2 Placement of the ViMove sensors

with the exception of the measurement of the vertical distance of the PSIS from the floor. Participants then returned 7–14 days later for a repeat assessment (Test 3) by Rater A. For participants with LBP, pain was recorded using three Numerical Rating Scales (worst pain =10, no pain =0), and the average of current, usual and worst pain over the previous 2 weeks was used [31]). Activity limitation was assessed using the Roland Morris Disability Questionnaire [32]. Pain and activity limitation were recorded on both assessment occasions.

Sample size

No existing data were available to inform sample size estimates. A sample of 60 adults aged 18–60 years ($n = 30$ with LBP, $n = 30$ without LBP) were recruited. This sample size would allow detection of a correlation of 0.44 or more between repeated measures in each group of 30, with an alpha of 0.05 and power of 0.8 [33]. Arbitrarily, we assumed this was an adequate threshold, as movement consistency that resulted in lower retest correlations would provide adequate evidence that the individual variations in movement patterns would be so large that patterns of movements would be too variable to be clinically interpretable. In addition, a sample size of 30 is recommended where researchers are studying differences between two sets of scores, as difference scores for samples of 30 or

more are likely to assume a normal distribution and thereby provide more adequate data for parametric tests.

Data analysis

Data on body position were sampled and recorded at approximately 20Hz for each of the five repetitions of flexion, extension and left and right lateral flexion movements. Averaged lumbar lordosis angle was recorded in standing over a 5-s period.

Peak angles were calculated for trunk and pelvic sensors to indicate maximum angular displacement at T12 (trunk movement) and S2 (pelvic/hip movement). Lumbar movement (movement between T12 to S2) was calculated by subtracting pelvic movement (movement of the lower sensor at S2) from trunk movement (movement of the upper sensor at T12). In addition to static posture and ROM, data on 'lumbar versus pelvic' contribution to flexion, extension and lateral flexion were collected during each movement. This is shown graphically in Fig. 3. A summary measure of this pattern of lumbar versus pelvic contribution to trunk movement (lumbo-pelvic rhythm) was estimated by calculating the percentage contribution of lumbar ROM to peak trunk ROM for flexion, extension and lateral flexion.

Statistical analysis

Participant demographics (gender, BMI, pain and activity limitations) were summarised.

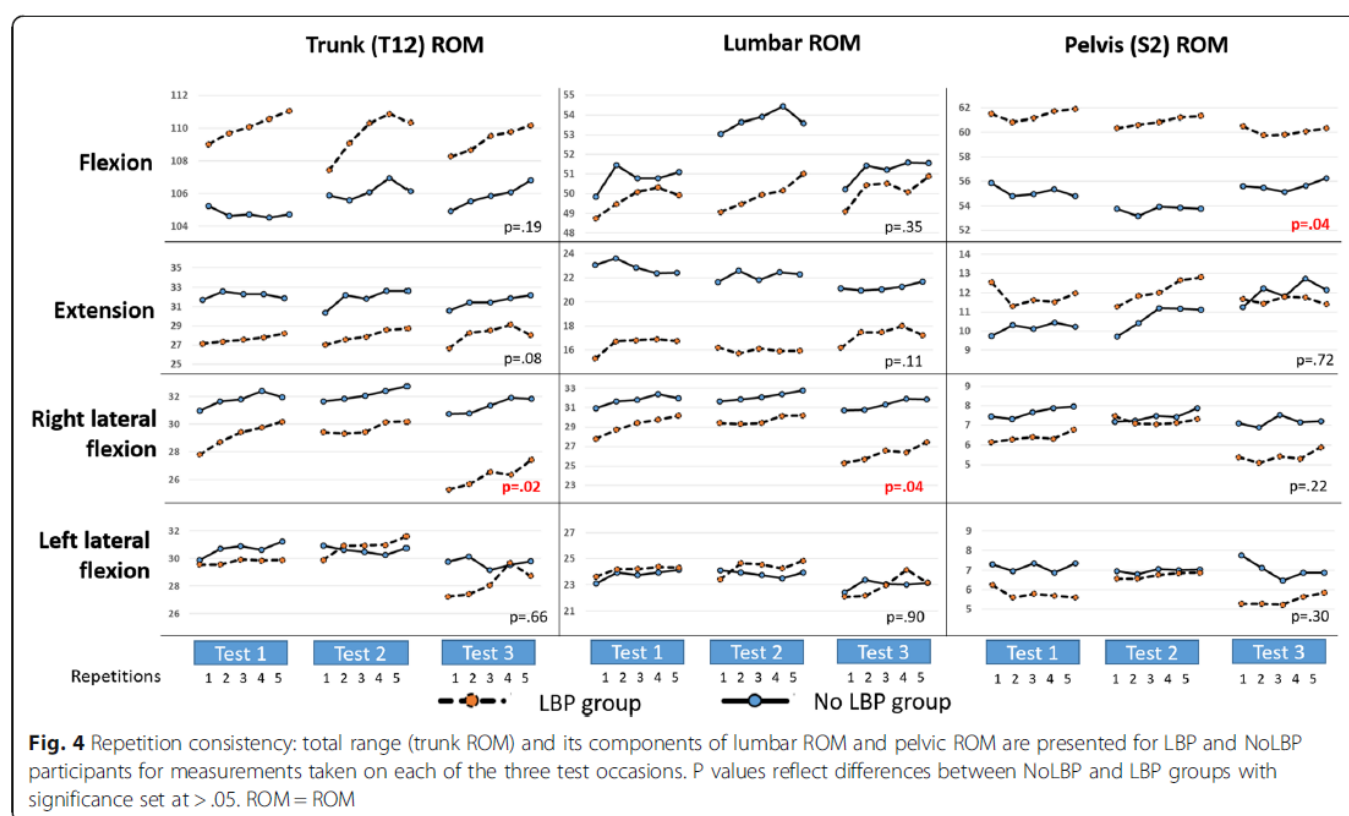### Comparing ROM for participants with and without LBP

Mean ROM scores for each of the repetitions (three tests each of five repetitions) for each movement, for LBP and NoLBP participants, were tested for differences between groups using a repeated measures ANOVA.

Consistency in repeated measurements

To examine the overall consistency in repeated movements, the standard deviation of all measurements of a movement for each participant was calculated. Differences in standard deviations between groups were tested using independent t-tests.

Within-test repeated movement consistency

Each of the three tests consisted of five repetitions for each movement. We considered that the best estimate of a person's ROM would most likely be an average of repeated measurements. Before commencing analysis of the magnitude of error in movement estimates, the five repetitions for Test 1 were examined to determine whether any of the repetitions were systematically different from others. Systematic variation for specific repetitions was assessed using a paired t-test to compare the mean for the first repetition to the mean for each of the other

Laird *et al. BMC Musculoskeletal Disorders* (2016) 17:403

Page 6 of 14

Fig. 4 Repetition consistency: total range (trunk ROM) and its components of lumbar ROM and pelvic ROM are presented for LBP and NoLBP participants for measurements taken on each of the three test occasions. P values reflect differences between NoLBP and LBP groups with significance set at > .05. ROM = ROM

flexion, where the standard deviation was significantly greater for the LBP group ($2.7° ± .25°$) compared to the NoLBP group ($1.98° ± .14°$).

Within-test repeated movement consistency

On examination of pairwise comparisons of repetitions 1 to 5, little evidence was found of significant effects attributable to repetition. Exceptions were lumbar flexion, and right lateral flexion (trunk and lumbar ROM) where (typically for both groups) ROM for the first repetition exhibited significantly smaller ROM than all other repetitions. Figure 4 shows similar patterns when other movements were considered. Consequently, repetition one was removed from subsequent analyses.

Movement consistency between tests
Lordosis and ROM

Table 2 summarises data for lordosis and ROM. Mean lordosis angles (across all three tests) for the two groups were not significantly different: $30.1° ± 11.1°$ for the NoLBP group and $27.8° ± 11.2°$ for the LBP group. The minimal detectable change based on the middle 90 % of scores (MDC_{90}) for measurements of lordosis taken on the same day was $±11.3°$ for the NoLBP group and $±8.8°$ for the LBP group, and approximately $±15°$ (both groups) for different-day comparisons.

Different-day measurements generally showed greater inconsistency than measurements taken on the same day. For example, trunk flexion for the LBP group would have to change by more than $± 8.7°$ (MDC_{90}) between tests on the same day for 90 % confidence that observed changes were not due to typical variation in these measurements. This increases to $± 10.2°$ change for tests on different days. An example of Bland Altman plots displaying the limits of agreement (95 % confidence intervals), for flexion, can be seen in Fig. 5. Trunk ROM measurement consistently showed greater stability compared to lumbar or pelvic ROM measurements for same-day and different-day comparisons. For example, for the LBP group, the MDC_{90} of trunk flexion for different-day tests was $10.2°$, compared to an MDC_{90} of $17°$ for lumbar ROM, and an MDC_{90} of $19°$ for pelvic ROM.

Lumbo-pelvic rhythm

Table 3 summarises the percentage contribution of lumbar ROM to trunk ROM (lumbo-pelvic rhythm). A significant difference between groups was seen for flexion (NoLBP 51.3 % ± 9.4 %, LBP 45.8 % ± 8.6 %, $F(1,63) = 4.20$, $p = .0445$). MDC_{90} scores for lumbo-pelvic rhythm suggest changes of relative lumbar versus pelvic contribution to trunk movement of between 9 and 15% would, for 90 % of tests, indicate true change for flexion and lateral flexion, while changes between 36 and 56 %

316

Table 2 Lordosis and ROM scores, and consistency between tests (degrees)

Movement	Region	Back pain status	ROM[a]				Inter-rater agreement (same-day, different raters) Test 1 versus Test 2		Intra-rater agreement (different-days, same rater) Test 1 versus Test 3	
			Test 1	Test 2	Test 3	Average for all 3 Tests	Mean & SD of differences between Test 1 & Test 2[b]	Minimal detectable change score	Mean & SD of differences between Test 1 & Test 3[b]	Minimal detectable change score
Lordosis[c]	Lumbar lordosis	NoLBP	−29.6 ± 11.2	−31.2 ± 11.3	−29.4 ± 10.8	−30.1 ± 11.1	1.5 ± 6.9	±11.3	−0.5 ± 9.1	±15.0
		LBP	−27.1 ± 11.6	−28.1 ± 10.5	−28.2 ± 11.8	−27.8 ± 11.2	1.0 ± 5.4	±8.8	0.2 ± 9.0	±14.8
	Trunk angle	NoLBP	−9.9 ± 5.7	−10.5 ± 5.1	−11.0 ± 4.2	−10.4 ± 5.0	0.6 ± 4.2	±6.9	1.2 ± 4.7	±7.7
		LBP	−9.5 ± 5.5	−9.4 ± 4.0	−9.9 ± 4.5	−9.6 ± 4.7	0.0 ± 3.7	±6.1	0.3 ± 3.4	±5.6
	Pelvic angle	NoLBP	19.7 ± 10.0	20.7 ± 9.6	18.4 ± 9.6	19.6 ± 9.7	−1.0 ± 5.5	±9.0	1.7 ± 7.2	±11.9
		LBP	17.6 ± 9.3	18.7 ± 10.8	18.4 ± 10.4	18.2 ± 10.1	−1.1 ± 5.8	±9.6	0.0 ± 7.9	±13.0
Flexion[c]	Trunk (T12) angle	NoLBP	104.9 ± 15.4	106.4 ± 15.5	105.8 ± 15.7	105.7 ± 15.4	−1.5 ± 4.1	±6.8	−0.4 ± 5.7	±9.3
		LBP	110.4 ± 14.3	110.2 ± 13.2	109.6 ± 13.1	110.1 ± 13.4	0.2 ± 5.3	±8.7	−0.4 ± 6.2	±10.2
	Lumbar range	NoLBP	51.2 ± 8.1	54.1 ± 8.9	50.9 ± 10.1	52.1 ± 9.1	−2.9 ± 6.6	±10.8	−0.4 ± 7.9	±13.0
		LBP	49.9 ± 11.6	50.1 ± 11.4	50.5 ± 11.5	50.2 ± 11.3	−0.2 ± 5.0	±8.4	−0.2 ± 8.4	±14.0
	Pelvic (S2) angle	NoLBP	54.9 ± 15.3	53.7 ± 14.6	55.8 ± 15.5	54.8 ± 15.0[d]	1.2 ± 5.0	±8.2	0.2 ± 6.6	±10.9
		LBP	61.0 ± 12.4	60.0 ± 14.4	61.2 ± 12.4	60.8 ± 13.2[d]	0.4 ± 7.1	±11.8	−1.0 ± 9.9	±16.6
Extension[c]	Trunk angle	NoLBP	32.3 ± 8.9	32.3 ± 9.5	31.7 ± 7.3	32.1 ± 8.6	0.0 ± 6.1	±10	−0.6 ± 6.0	±9.9
		LBP	27.1 ± 7.0	26.2 ± 7.6	27.4 ± 6.2	26.9 ± 7.0	−0.9 ± 3.9	±6.3	1.0 ± 4.4	±7.2
	Lumbar range	NoLBP	22.8 ± 13.9	22.3 ± 12.2	21.2 ± 12.4	22.1 ± 12.8	−0.5 ± 7.6	±12.5	−2.2 ± 11.3	±18.6
		LBP	15.1 ± 8.5	15.2 ± 10.6	15.6 ± 7.2	15.2 ± 8.9	0.1 ± 5.5	±9.0	1.4 ± 3.8	±6.2
	Pelvic angle	NoLBP	11.3 ± 8.5	11.5 ± 8.2	12.7 ± 9.3	11.8 ± 8.6	0.2 ± 5.9	±9.7	1.8 ± 8.4	±13.8
		LBP	12.3 ± 8.4	11.3 ± 9.7	12.0 ± 7.8	11.9 ± 8.7	−1.1 ± 6.2	±10.1	−0.3 ± 4.6	±7.6
Left lateral flexion[c]	Trunk angle	NoLBP	31.2 ± 6.6	30.7 ± 6.0	29.9 ± 5.4	−30.6 ± 6	−0.5 ± 4.1	±6.9	−0.8 ± 4.9	±8.1
		LBP	29.8 ± 6.0	31.1 ± 6.5	28.5 ± 6.1	−29.9 ± 6.2	1.3 ± 3.9	±6.5	−0.7 ± 3.4	±5.7
	Lumbar range	NoLBP	24.1 ± 4.7	23.9 ± 4.3	23.3 ± 4.6	−23.8 ± 4.5	−0.2 ± 3.3	±5.5	−0.2 ± 3.9	±6.6
		LBP	24.3 ± 5.3	24.6 ± 5.9	23.1 ± 5.9	−24.1 ± 5.7	0.3 ± 3.5	±5.8	−1.1 ± 3.2	±5.3
	Pelvic angle	NoLBP	7.3 ± 4.1	7.1 ± 3.8	6.9 ± 3.6	−7.4 ± 3.8	−0.2 ± 2.5	±4.2	−0.5 ± 2.7	±4.5
		LBP	5.7 ± 2.8	6.8 ± 3.7	5.5 ± 3.5	−6.0 ± 3.4	1.1 ± 2.6	±4.3	0.3 ± 2.4	±4.1

317

Table 2 Lordosis and ROM scores, and consistency between tests (degrees) *(Continued)*

Right lateral flexion[c]	Trunk angle	NoLBP	31.9 ± 6.0	32.4 ± 6.5	31.6 ± 6.5	32 ± 6.2	−0.5 ± 2.9	±4.9	−0.2 ± 2.7	±4.5
		LBP	29.5 ± 5.1	29.8 ± 5.1	26.5 ± 5.7	28.8 ± 5.4	−0.3 ± 4.0	±6.6	−2.6 ± 3.5	±5.8
	Lumbar range	NoLBP	24.4 ± 4.6	24.9 ± 4.5	24.7 ± 4.6	24.7 ± 4.5	−0.5 ± 2.4	±4.0	−0.7 ± 3.1	±5.2
		LBP	23.2 ± 5.2	22.8 ± 4.6	21.3 ± 5.7	22.3 ± 5.6	0.4 ± 3.0	±5.1	1.9 ± 2.6	±4.3
	Pelvic angle	NoLBP	7.7 ± 3.9	7.7 ± 4.0	7.1 ± 3.8	7.5 ± 3.9	0.0 ± 2.5	±4.1	0.6 ± 2.7	±4.5
		LBP	6.4 ± 2.9	7.1 ± 3.3	5.4 ± 3.3	6.4 ± 3.2	−0.7 ± 3.1	±5.1	0.7 ± 2.8	±4.8

Legend: *LBP* LBP group, *NoLBP* no LBP group, *ROM* ROM
[a]ROM and standard deviation data represent the group mean and standard deviation (SD). The standard deviation indicates the magnitude of differences between individuals within the group
[b]These data are derived from the difference in ROM between tests for each individual, (i.e., Test 1 versus 2, Test 1 versus 3) then calculating group mean and SD of the difference scores
[c]See Table 4 for numbers (n) of participants in each group
[d]Indicates significant difference between groups

Laird *et al. BMC Musculoskeletal Disorders* (2016) 17:403

Page 8 of 14

318

Laird *et al. BMC Musculoskeletal Disorders* (2016) 17:403

Page 9 of 14

Fig. 5 Bland-Altman plots for trunk, lumbar and pelvic lumbar flexion

are required to be similarly sure of true change for extension (see Table 4).

Inter-rater and intra-rater reliability

ICCs (Table 4) across all measured characteristics averaged $r = .88$ (range .80 to .98) for same-day inter-rater reliability and $r = .85$ (range .67 to .97) for different-day intra-rater reliability. All ICCs were below $P = .005$. The results for both intra and inter rater agreement demonstrate good to excellent agreement for almost all comparisons [35].

Discussion
Overview
In this study, we assessed people with and without LBP and determined the consistency in measurements of their standing lordosis, active movement range and lumbo-pelvic rhythm over two tests on the same day and a third test 7–14 days later. We found that the LBP and NoLBP participants had similar standing lordosis angles and ROM, with the exception of greater pelvic ROM in flexion (LBP group), and greater trunk and lumbar ROM in right lateral flexion (NoLBP group). Although the LBP group demonstrated similar trunk ROM during flexion, this appeared to have been achieved through relatively greater pelvis/hip contribution. In addition, we found no significant difference in movement consistency between the NoLBP and LBP groups. Lastly, we found good to excellent inter-rater (same day) and intra-rater (different days)

reliability for most movements, with MDC_{90} estimates for expected variation between tests in the order of 5–15° and MDC_{90} estimates for lumbar contribution to lumbo-pelvic rhythm in flexion and lateral flexion that ranged from 8 to 15 %. In contrast, the MDC_{90} estimates for lumbar contributions to extension showed an expected variability that was in the order of 36–56 % and these findings may limit the clinical utility of monitoring changes in lumbar contribution to extension.

ROM and variability comparisons
A recent meta-analysis identified that, on average, people with chronic LBP have less lumbar ROM than people who do not have LBP [22]. Our data did not demonstrate any significant difference between groups in lumbar ROM, although there was a trend towards there being more hip and less lumbar spine involved in achieving flexion ROM for people with LBP (Fig. 4). In addition, we noted less lumbar extension in people with LBP although this also did not achieve significance. These observations warrant confirmation through studies of independent samples of people with and without LBP.

Clinical utility depends on how much change a clinician expects to see and knowledge of how much change is due to biological variation and measurement error. ROM data for all components (i.e., trunk, lumbar and pelvic ROM) of flexion and lateral flexion, and for extension (trunk ROM only) indicate sufficient stability to be potentially clinically

Table 3 Lumbo-pelvic rhythm (expressed as the percentage of lumbar contribution to trunk ROM) and consistency between tests

Movement	Back pain status	Average % Lumbar movement for each test[a]				Inter-rater agreement (same-day, different raters)		Intra-rater agreement (different-days, same rater)	
		Test 1	Test 2	Test 3	Average for all 3 Tests	Mean & standard deviation of differences[b] between Test 1 vs Test 2	Minimal detectable change (MDC$_{90}$)	Mean & standard deviation of differences[b] between Test 1 vs Test 3	Minimal detectable change (MDC$_{90}$)
Flexion[c]	NoLBP	51.9 % ± 9.6 %	50.0 % ± 9.0 %	52.0 % ± 9.6 %	51.3 % ± 9.4 %	1.9 % ± 5.5 %	9.1 %	0.8 % ± 7.0 %	11.5 %
	LBP	45.4 % ± 8.9 %	45.6 % ± 8.6 %	46.4 %10.7 %	45.8 % ± 8.6 %	0.2 % ± 5.9 %	8.5 %	0.5 % ± 9.4 %	15.5 %
Extension[c]	NoLBP	68.4 % ± 34.0 %	68.9 % ± 31.2 %	66.6 % ± 33.2 %	68.0 % ± 32.3 %	0.5 % ± 22 %	36.3 %	2.6 % ± 34.2 %	56.2 %
	LBP	58.2 % ± 30.2 %	56.2 % ± 30.6 %	59.0 % ± 29.7 %	56.9 % ± 33.7 %	2.0 % ± 25.2 %	41.4 %	1.1 % ± 31.8 %	52.3 %
Left lateral flexion[c]	NoLBP	78.5 % ± 10.0 %	78.7 % ± 9.0 %	79.0 % ± 9.8 %	78.6 % ± 9.5 %	0.2 % ± 7.3 %	12.0 %	0.6 % ± 7.2 %	11.8 %
	LBP	81.6 % ± 8.2 %	79.2 % ± 10.2 %	81.1 % ± 10.4 %	80.6 % ± 9.6 %	2.4 % ± 7.3 %	12.0 %	1.6 % ± 7.2 %	11.8 %
Right lateral flexion[c]	NoLBP	77.4 % ± 9.5 %	78.2 % ± 8.8 %	79.3 % ± 8.3 %	78.0 % ± 9.1 %	0.7 % ± 6.8 %	11.2 %	2.3 % ± 6.3 %	10.4 %
	LBP	78.4 % ± 9.4 %	76.6 % ± 9.4 %	80.2 % ± 11.6 %	78.3 % ± 10.0 %	1.8 % ± 8.2 %	13.5 %	1.0 % ± 8.9 %	14.6 %

[a]Calculated by dividing lumbar ROM over trunk ROM then converting to percentage
[b]See explanation in Table 3 footnote regarding methods used in calculating the SD of difference scores
[c]See Table 4 for numbers (n) of participants in each group

Laird *et al. BMC Musculoskeletal Disorders* (2016) 17:403

Page 11 of 14

Table 4 Inter-rater and Intra-rater reliability (Intraclass Correlation Coefficients using mean of repetitions 2–5)

Interrater	NoLBP subjects				LBP subjects			
	n =	T12 angle	Pelvic angle	Lumbar ROM	n =	T12 angle	Pelvic angle	Lumbar ROM
Flexion	32	.98 (.96 to .99)	.97 (.94 to .99)	.80 (.56 to .91)	32	.96 (.92 to .98)	.92 (.84 to .96)	.95 (.90 to .98)
Extension	31	.88 (.74 to .94)	.87 (.72 to .93)	.91 (.81 to .96)	28	.95 (.90 to .98)	.77 (.52 to .89)	.94 (.87 to .97)
Lordosis	33	.83 (.65 to .91)	.91 (.83 to .96)	.90 (.79 to .95)	32	.83 (.65 to .92)	.91 (.81 to .96)	.94 (.87 to .97)
Lateral Flexion left	33	.88 (.76 to .94)	.89 (.77 to .94)	.84 (.68 to .92)	32	.89 (.76 to .94)	.79 (.56 to .90)	.89 (.78 to .95)
Lateral flexion right	33	.94 (.88 to .97)	.88 (.72 to .95)	.92 (.84 to .96)	32	.82 (.64 to .91)	.67 (.33 to .83)	.89 (.79 to .95)
Intrarater	NoLBP subjects				LBP subjects			
Flexion	28	.97 (.93 to .99)	.95 (.90 to .98)	.86 (.68 to .94)	25	.95 (.89 to .98)	.86 (.69 to .94)	.86 (.69 to .94)
Extension	28	.84 (.64 to .92)	.71 (.38 to .86)	.79 (.54 to .90)	21	.94 (.88 to .98)	.67 (.25 to .86)	.94 (.87 to .97)
Lordosis	30	.71 (.40 to .86)	.84 (.68 to .93)	.81 (.59 to .91)	25	.89 (.74 to .95)	.82 (.60 to .92)	.85 (.65 to .93)
Lateral Flexion left	30	.77 (.53 to .89)	.85 (.69 to .93)	.76 (.49 to .89)	25	.92 (.82 to .96)	.83 (.61 to .92)	.92 (.81 to .96)
Lateral flexion right	30	.95 (.90 to .98)	.88 (.75 to .94)	.89 (.77 to .95)	25	.85 (.46 to .94)	.70 (.34 to .87)	.92 (.68 to .97)

Legend: ROM = ROM Intraclass correlation co-efficients (ICC 2,2) and 95 % confidence intervals

useful with $MDC_{90's}$ of 5–15° (flexion), 4–8° (lateral flexion) and 6–10° (trunk extension) indicating high probability of true change. However, changes to lumbar and pelvic extension were associated with higher retest variations, with $MDC_{90's}$ of 10–14° (pelvic movements) and up to 19° (lumbar spine movements). These findings may limit the clinical utility of using changes in lumbar spine extension ROM to monitor progress.

Trunk angle measurements were generally associated with smaller retest variations than lumbar or pelvic angle measurements, which may inspire the argument that trunk ROM is the more sensitive and potentially valuable outcome measure. Our data indicate however that people with LBP appear to retain full flexion ROM by increasing pelvic/hip movement while limiting lumbar contribution.

Inter-rater (same day) differences between tests were generally smaller than intra-rater (different day) differences. This is a common finding in reliability studies and is likely to be due to a combination of factors that occur between measurement days, such as normal biological variations, minor variations to experimental conditions and possible environmental factors. We studied intra-rater different-day measurements as this reflects common clinical practice, making the results relevant to clinical decision-making.

Within-test repeated movement consistency

The first repetition of flexion and right lateral flexion movements was significantly different to subsequent repetitions, with similar, non-statistically significant, patterns seen for other movements (see Fig. 4). As a consequence, we used repetitions 2–5 for analysis of movement consistency. This renders the study results relevant to clinicians who allow clients to practice the test before commencing measurement. The first repetition of a test may be affected by apprehension,

uncertainty about what is required, fear of pain, movement stiffness, and distraction or inattention, to name only some of the possible factors that might explain this aspect of our data.

Lordosis

Lumbar lordosis angles are of clinical interest in assessing spinal alignment and postural archetypes. A wide range of group mean lordosis angles, measured by skin surface techniques, have been reported. A recent review of nine studies reported mean lordosis angles ranging from 23° to 55° [22]. Mean (±SD) standing lordosis, measured in this study, ranged from 27° to 31° ± 11°, without any significant differences between LBP and NoLBP groups. In our data, relatively large variability in standing lordosis angles was seen between tests on both the same day and on different days with MDC_{90} scores ranging from 9° to 11° for tests on the same day and up to 15° for tests on different days. This variability may be a test artifact related to precision in sensor placement or it may be true biological variability. We were very particular in attempting precise sensor repositioning in repeated tests and it is unlikely that greater accuracy in sensor placement would be expected in typical clinical practice.
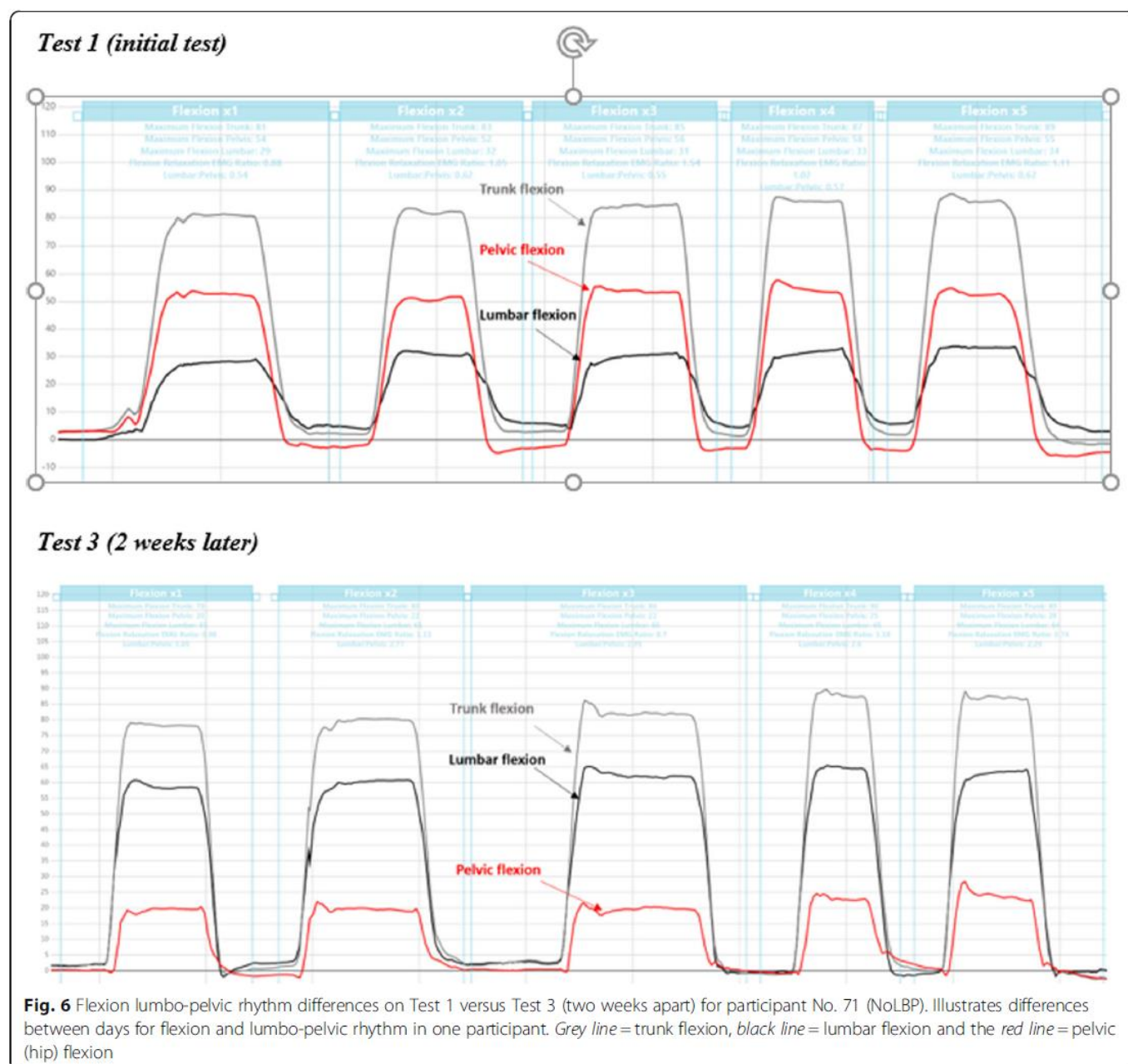
Lumbo-pelvic rhythm

Various patterns of lumbo-pelvic movement have been described but few patterns have been measured or reported as outcomes. Clinicians are interested in identifying the contributions to trunk movement from hip movement and lumbar spine movement. It has been proposed that when extremes of lumbar or pelvic contribution to trunk flexion are corrected, associated pain can be reduced [10, 11]. This study showed relatively greater hip compared to lumbar contribution for the LBP group. We

speculate that this maybe a compensatory mechanism as a response to reduced lumbar ROM. A recent meta-analysis (six studies) of typical lumbo-pelvic rhythm showed similar but non-significant findings of reduced lumbar contribution to trunk flexion [22]. Although lumbo-pelvic rhythm has been reported using a lumbar/pelvic angle ratio, we consider that percentage lumbar contributions to trunk movement are easier to visualise and circumvent the complexities associated with interpretation of ratios (that can be affected by both the numerator and the denominator). If trunk movement occurs entirely at the lumbar spine, the lumbo-pelvic rhythm will be 100 %, while a person who bends with the pelvis/hips and without lumbar spine movement will score 0 %.

In our data (Table 3), mean lumbar contribution to trunk flexion ranged from 46 % ± 9 % to 51 % ± 9 %. This is closely consistent with Kim et al. [15] who reported similar mean lumbar contributions to trunk flexion of 45 % ± 9 % to 49 % ± 9 %.

Considerable test-to-test variability in the percentage contribution of pelvic and lumbar movement to trunk flexion was seen in our data for a small number of participants. An example of this variable motor control of lumbar and pelvic movement contribution, while maintaining relatively consistent trunk ROM, is shown in Fig. 6. This NoLBP participant demonstrated an increase in lumbar contribution to trunk flexion from an initial 38 to 74 %, despite little difference in overall trunk ROM of around 80°.

Fig. 6 Flexion lumbo-pelvic rhythm differences on Test 1 versus Test 3 (two weeks apart) for participant No. 71 (NoLBP). Illustrates differences between days for flexion and lumbo-pelvic rhythm in one participant. *Grey line* = trunk flexion, *black line* = lumbar flexion and the *red line* = pelvic (hip) flexion

Laird *et al. BMC Musculoskeletal Disorders* (2016) 17:403

Page 13 of 14

Limitations of this study

Using a skin surface measurement technique to measure movement has the advantage of being non-invasive and possible within a typical clinical setting. However, any skin surface measurement technique has to be vigilant for artefacts that can occur due to issues such as skin buckling, sensor placement error, loss of sensor adherence to skin, etc. Excessive adipose tissue and skin buckling can alter the orientation of the surface-mounted movement sensor in some people, although simple observation can screen for this type of error. Skin surface measurement also has the inherent issue of sensor placement error, with relatively poor reliability of manual palpation of bony landmarks [30]. However we attempted to reduce this error by additional linear measurement to reduce placement error for subsequent tests.

There is a significant difference between LBP and NoLBP groups for age, with the LBP group being older on average. Other studies have shown that ROM diminishes with age but these changes are more visible in the 5th and 6th decades [36]. While it is possible that age-related differences between groups may account for reduced movement in the LBP group (trunk and lumbar right lateral flexion), it is unlikely age would explain increased ROM (pelvic flexion) or the altered lumbo-pelvic rhythm (where trunk ROM was the similar for both groups).. A significant difference for activity limitation was seen between Test 1 versus Test 3 for the LBP group but the difference between scores was 1.5 on the RMDQ and is unlikely to be clinically meaningful.

Rotational measurements were not technically possible with motion sensors at the time of testing but advances now allow for testing axial rotation. Further research should include rotation.

This study was not powered to test for differences between subgroups within the LBP population (pain intensity, presence of leg pain, mechanism of injury, movement pattern, aggravating activities etc.) so it possible that various subgroup definitions may demonstrate different results.

We conducted multiple ANOVAs when studying the differences in ROM for those with and without LBP, and retained our alpha level at .05 for all comparisons. Some observed differences between groups may therefore be chance findings, and the study findings warrant testing in independent studies.

A further limitation may be the single intra-rater comparison. Further studies could include multiple intra-rater comparisons to increase the robustness of extrapolating these results to other clinicians.

Conclusion

This study compared the consistency of lumbar lordosis, lumbo-pelvic range of movement (ROM) and lumbo-pelvic rhythm in people with and without low back pain, over three test sessions: two tests on the same day and a third test, 1 to 2 weeks later. There was little difference between the LBP and NoLBP groups for lordosis angle, and most ROM conditions, with the exception of greater pelvic flexion and reduced trunk and lumbar right lateral flexion ROM. Significantly reduced relative lumbar contribution to flexion lumbo-pelvic rhythm was seen in the LBP group. Movement consistency between each test was described by using MDC_{90} to measure between-test differences. Mean lumbar lordosis angles of approximately $30°$ required around $10°$ change to have 90 % confidence of seeing true change between same-day tests and $15°$ for different-day tests. ROM tests showed relatively greater consistency with changes ranging from 5 to$15°$ between tests required to similarly identify true change. Lumbo-pelvic rhythm changes of $> 8–15$ % lumbar contribution to flexion and lateral flexion trunk ROM indicated probable change, while a larger change of $>36–56$ % would be needed to be confident of change to an extension lumbo-pelvic rhythm.

Additional file

Additional file 1: Description and details of measured lumbo-pelvic kinematics. Description of data: Provides information about movements tested, sensor placement and instruction to the subject. (DOCX 12 kb)

Abbreviations

LBP: Low back pain; NoLBP: Participants without low back pain; RMDQ: Roland Morris Disability Questionnaire; ROM: ROM

Authors' contributions

RL contributed to data collection. RL was the main author of this paper, with concept, writing, data analysis, interpretation, draft revision and gave approval of the final manuscript. JK provided concept guidance, statistical direction, analysis, draft revision and gave approval of the final manuscript. PK provided concept guidance, statistical analysis, draft revision and gave approval of the final manuscript. RL, JK and PK agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Competing interests

No benefits in any form have been, or will be, received for this study from a commercial party related directly or indirectly to the subject of this paper. This paper does not contain information about drugs. The authors do not hold stocks or shares in any company that might be directly or indirectly affected by this study. No patents have been applied for or received due to the content of this paper and there are no non-financial competing interests associated with this paper.

Laird *et al. BMC Musculoskeletal Disorders* (2016) 17:403

Page 14 of 14

Author details
[1]Department of Physiotherapy, Monash University, PO Box 527, Frankston, VIC 3199, Australia. [2]School of Physiotherapy and Exercise Science, Curtin University, Perth, Australia. [3]Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark. [4]380 Springvale Rd, Forest Hill, 3131 Melbourne, VIC, Australia.

References
1. Vos T, Flaxman AD, Naghavi M, Lozano R, Michaud C, Ezzati M, Shibuya K, Salomon JA, Abdalla S, Aboyans V, et al. Years lived with disability (YLDs) for 1160 sequelae of 289 diseases and injuries 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet. 2012;380(9859):2163–96.
2. Pincus T, Kent P, Bronfort G, Loisel P, Pransky G, Hartvigsen J. Twenty-five years with the biopsychosocial model of low back pain – is it time to celebrate? A report from the Odense Forum XII. Spine. 2013;38(24):2118–23.
3. Lariviere C, Gagnon D, Loisel P. The effect of load on the coordination of the trunk for subjects with and without chronic low back pain during flexion-extension and lateral bending tasks. Clin Biomech. 2000;15(6):407–16.
4. Tafazzol A, Arjmand N, Shirazi-Adl A, Parnianpour M. Lumbopelvic rhythm during forward and backward sagittal trunk rotations: combined in vivo measurement with inertial tracking device and biomechanical modeling. Clin Biomech. 2014;29:7+.
5. Esola MA, McClure PW, Fitzgerald GK, Siegler S. Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain. Spine. 1996;21(1):71–8.
6. Lee RYW, Wong TKT. Relationship between the movements of the lumbar spine and hip. Hum Mov Sci. 2002;21(4):481–94.
7. McClure PW, Esola M, Schreier R, Siegler S. Kinematic analysis of lumbar and hip motion while rising from a forward, flexed position in patients with and without a history of low back pain. Spine. 1997;22(5):552–8.
8. Paquet N, Malouin F, Richards C. Hip-spine movement interaction and muscle activation patterns during sagittal trunk movements in low back pain patients. Spine. 1994;15(5):596–603.
9. Porter JL, Wilkinson A. Lumbar-hip flexion motion. A comparative study between asymptomatic and chronic low back pain in 18- to 36-year-old men. Spine. 1997;22(13):1508–13. discussion 1513–1504.
10. O'Sullivan P. Diagnosis and classification of chronic low back pain disorders: maladaptive movement and motor control impairments as underlying mechanism. Man Ther. 2005;10(4):242–55.
11. Sahrmann S. Diagnosis and treatment of movement impairment syndromes. 2002.
12. Van Dillen LR, Sahrmann SA, Norton BJ, Caldwell CA, McDonnell MK, Bloom N, Van Dillen LR, Sahrmann SA, Norton BJ, Caldwell CA, et al. The effect of modifying patient-preferred spinal movement and alignment during symptom testing in patients with low back pain: a preliminary report. Arch Phys Med Rehabil. 2003;84(3):313–22.
13. Ikeda K, McGill S. Can altering motions, postures, and loads provide immediate low back pain relief: a study of 4 cases investigating spine load, posture, and stability. Spine. 2012;37(23):E1469–75.
14. Pynt J, Mackey MG, Higgs J. Kyphosed seated postures: extending concepts of postural health beyond the office. J Occup Rehabil. 2008;18(1):35–45.
15. Kim MH, Yi CH, Kwon OY, Cho SH, Cynn HS, Kim YH, Hwang SH, Choi BR, Hong JA, Jung DH. Comparison of lumbopelvic rhythm and flexion-relaxation response between 2 different low back pain subtypes. Spine. 2013;38(15):1260–7.
16. Hodges PW, Coppieters MW, MacDonald D, Cholewicki J. New insight into motor adaptation to pain revealed by a combination of modelling and empirical approaches. Eur J Pain. 2013;17(8):1138–46.
17. Neblett R, Mayer TG, Brede E, Gatchel RJ. Correcting abnormal flexion-relaxation in chronic lumbar pain: responsiveness to a new biofeedback training protocol. Clin J Pain. 2010;26(5):403–9.
18. Brumagne S, Cordo P, Lysens R, Verschueren S, Swinnen S. The role of paraspinal muscle spindles in lumbosacral position sense in individuals with and without low back pain. Spine. 2000;25(8):989–94.
19. Descarreaux M, Blouin J-S, Teasdale N. Repositioning accuracy and movement parameters in low back pain subjects and healthy control subjects. Eur Spine J. 2005;14(2):185–91.
20. Kent P, Laird R, Haines T. The effect of changing movement and posture using motion-sensor biofeedback, versus guidelines-based care, on the clinical outcomes of people with sub-acute or chronic low back pain-a multicentre, cluster-randomised, placebo-controlled, pilot trial. BMC Musculoskelet Disord. 2015;16:131–50.
21. Long A, Donelson R, Fung T. Does it matter which exercise? A randomized control trial of exercise for low back pain. Spine. 2004;29(23):2593–602.
22. Laird R, Gilbert J, Kent P, Keating J. Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis. BMC Musculoskelet Disord. 2014;15(1):229.
23. Laird R, Kent P, Keating J. Modifying patterns of movement in people with low back pain - does it help? A systematic review. BMC Musculoskelet Disord. 2012;13:169.
24. O'Sullivan KJ, O'Sullivan L, Campbell A, O'Sullivan P, Dankaerts W. Towards monitoring lumbo-pelvic posture in real-life situations: concurrent validity of a novel posture monitor and a traditional laboratory-ased motion analysis system. Man Ther. 2012;17:77–83.
25. Ribeiro DC, Sole G, Abbott JH, Milosavljevic S. Cumulative postural exposure measured by a novel device: a preliminary study. Ergonomics. 2011;54(9):858–65.
26. Bauer CM, Baumgartner L, Schelldorfer S, Ernst M, Lawrence M. Technical validation of a new movement therapy system for treatment of low back pain. Gait Posture. 2012;36:S40.
27. Ha TH, Saber-Sheikh K, Moore AP, Jones MP. Measurement of lumbar spine range of movement and coupled motion using inertial sensors - A protocol validity study. Man Ther 2013;18(1):87–91.
28. Manniche C, Asmussen K, Lauritsen B, Vinterberg H, Kreiner S, Jordan A. Low back pain rating scale: validation of a tool for assessment of low back pain. Pain. 1994;57(3):317–26.
29. Charry E, Umer M, Taylor S. Design and validation of an ambulatory inertial system for 3-D measurements of low back movements. Proceedings of Seventh International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP 2011) IEEE Conference Publications (http://ieeexplore.ieee.org/document/6146618/). Accessed 2016.
30. Kilby J, Heneghan NR, Maybury M. Manual palpation of lumbo-pelvic landmarks: a validity study. Man Ther. 2012;17(3):259–62.
31. Chien CW, Bagraith KS, Khan A, et al. Comparative responsiveness of verbal and numerical rating scales to measure pain intensity in patients with chronic pain. J Pain. 2013;14:1653–62.
32. Roland M, Fairbank J. The Roland-Morris disability questionnaire and the oswestry disability questionnaire. Spine. 2000;25(24):3115–24.
33. StataCorp. Stata Statistical Software: Release 12. College Station: StataCorp LP; 2011.
34. Mokkink LB, Terwee CB, Patrick DL, Alonso J, Stratford PW, Knol DL, Bouter LM, de Vet HCW. The COSMIN study reached international consensus on taxonomy, terminology, and definitions of measurement properties for health-related patient-reported outcomes. J Clin Epidemiol. 2010;63(7):737–45.
35. Portney LG, Watkins MP. Foundations of clinical research: applications to practice. 3rd ed. New Jersey: Pearson Prentice Hall; 2009.
36. Intolo P, Milosavljevic S, Baxter DG, Carman AB, Pal P, Munn J, Intolo P, Milosavljevic S, Baxter DG, Carman AB, et al. The effect of age on lumbar range of motion: a systematic review. Man Ther. 2009;14(6):596–604.

9.12. Appendix L: Description and details of measured lumbo-pelvic kinematics for Laird et al (2016)

Description	Movement characteristics recorded	Details and instructions
Lordosis in neutral defined as usual standing posture	Trunk (T12) and pelvis (S2) angles	Stand for 10 seconds, sensors calibrated relative to vertical
Standing pelvic tilt angle and ROM	Angle of pelvis in neutral (pelvis at 'zero'), full anterior and full posterior tilt	Move from neutral to full anterior tilt, followed by full posterior tilt
Flexion ROM (lumbar and hip)	Angle of trunk, pelvis and lumbar spine (T12 angle minus S2 angle),	Move from neutral standing to full flexion, hold for 3 seconds, return to neutral
Extension ROM	Angles of trunk, lumbar spine and pelvis	Move from neutral standing to full extension, hold for 3 seconds, return to neutral
Lateral flexion ROM	Angles of trunk, pelvis and lumbar spine	Move from neutral (zero) standing to full lateral flexion, hold 3 seconds, return to neutral, repeat bilaterally

Legend: ROM= Range of motion

9.13. Appendix M: Lordosis and ROM scores, and consistency within and between tests (degrees) – updated from publication

Movement	Region	Back pain status	ROM* Test 1	Test 2	Test 3	Average for all 3 Tests	Within test variability (range between min to max score within tests) Average for all 3 Tests	Minimal detectable change score	Inter-rater agreement (same-day, different raters) Test 1 versus Test 2 Mean & SD of differences between Test 1 & Test 2**	Minimal detectable change score	Intra-rater agreement (different-days, same rater) Test 1 versus Test 3 Mean & SD of differences between Test 1 & Test 3**	Minimal detectable change score
Lordosis[†]	Lumbar lordosis	NoLBP	-29.6 ± 11.2	-31.2 ± 11.3	-29.4 ± 10.8	-30.1±11.1			1.5 ± 6.9	± 11.3	-0.5 ± 9.1	± 15.0
		LBP	-27.1 ± 11.6	-28.1 ± 10.5	-28.2 ± 11.8	-27.8 ± 11.2			1.0 ± 5.4	± 8.8	0.2 ± 9.0	± 14.8
	Trunk angle	NoLBP	-9.9 ± 5.7	-10.5 ± 5.1	-11.0 ± 4.2	-10.4 ± 5.0			0.6 ± 4.2	± 6.9	1.2 ± 4.7	± 7.7
		LBP	-9.5 ± 5.5	-9.4 ± 4.0	-9.9± 4.5	-9.6 ± 4.7			0.0 ± 3.7	± 6.1	0.3 ± 3.4	± 5.6
	Pelvic angle	NoLBP	19.7 ± 10.0	20.7 ± 9.6	18.4 ± 9.6	19.6 ± 9.7			-1.0 ± 5.5	± 9.0	1.7 ± 7.2	± 11.9
		LBP	17.6 ± 9.3	18.7 ± 10.8	18.4 ± 10.4	18.2 ±10.1			-1.1 ± 5.8	± 9.6	0.0 ± 7.9	± 13.0
Flexion[†]	Trunk (T12) angle	NoLBP	104.9 ± 15.4	106.4 ± 15.5	105.8 ± 15.7	105.7 ± 15.4	4.9±2.6	± 4.3	-1.5 ± 4.1	± 6.8	-0.4 ± 5.7	± 9.3
		LBP	110.4 ± 14.3	110.2 ± 13.2	109.6 ± 13.1	110.1 ± 13.4	4.6±2.9	± 4.8	0.2 ± 5.3	± 8.7	-0.4 ± 6.2	± 10.2
	Lumbar range	NoLBP	51.2 ± 8.1	54.1 ± 8.9	50.9 ± 10.1	52.1 ± 9.1	3.5±2.1	± 3.5	-2.9 ± 6.6	± 10.8	-0.4 ± 7.9	± 13.0
		LBP	49.9 ± 11.6	50.1 ± 11.4	50.5 ± 11.5	50.2 ± 11.3	3.4±2.6	± 4.3	-0.2 ± 5.0	± 8.4	-0.2 ± 8.4	± 14.0
	Pelvic (S2) angle	NoLBP	54.9 ± 15.3	53.7 ± 14.6	55.8 ± 15.5	54.8 ± 15.0‡	3.5±2.1	± 3.5	1.2 ± 5.0	± 8.2	0.2 ± 6.6	± 10.9
		LBP	61.0 ± 12.4	60.0 ± 14.4	61.2 ± 12.4	60.8 ± 13.2‡	3.6±1.9	3.1	0.4 ± 7.1	± 11.8	-1.0 ± 9.9	± 16.6
Extension[†]	Trunk angle	NoLBP	32.3 ± 8.9	32.3 ± 9.5	31.7 ± 7.3	32.1 ± 8.6	3.1±2.2	± 3.6	0.0 ± 6.1	± 10	-0.6 ± 6.0	± 9.9
		LBP	27.1 ± 7.0	26.2 ± 7.6	27.4 ± 6.2	26.9 ± 7.0	3.9±2.1	± 3.5	-0.9 ± 3.9	± 6.3	1.0 ± 4.4	± 7.2
	Lumbar range	NoLBP	22.8 ± 13.9	22.3 ± 12.2	21.2± 12.4	22.1 ± 12.8	3.1±2.2	± 3.6	-0.5 ± 7.6	± 12.5	-2.2 ± 11.3	± 18.6
		LBP	15.1 ± 8.5	15.2 ± 10.6	15.6 ± 7.2	15.2 ± 8.9	3.5±2.3	± 3.8	0.1 ± 5.5	± 9.0	1.4 ± 3.8	± 6.2
	Pelvic angle	NoLBP	11.3 ± 8.5	11.5 ± 8.2	12.7 ± 9.3	11.8 ± 8.6	2.6±1.7	± 2.8	0.2 ± 5.9	± 9.7	1.8 ± 8.4	± 13.8
		LBP	12.3 ± 8.4	11.3 ± 9.7	12.0 ± 7.8	11.9 ± 8.7	3.0±2.0	3.3	-1.1 ± 6.2	± 10.1	-0.3 ± 4.6	± 7.6

Left lateral flexion†	**Trunk angle**	NoLBP	**31.2 ± 6.6**	**30.7 ± 6.0**	**29.9 ± 5.4**	**-30.6 ± 6**	**3.4±2.3**	**± 3.8**	**-0.5 ± 4.1**	**± 6.9**	**-0.8 ± 4.9**	**± 8.1**
		LBP	**29.8 ± 6.0**	**31.1 ± 6.5**	**28.5 ± 6.1**	**-29.9 ± 6.2**	**3.3±2.1**	**± 3.5**	**1.3 ± 3.9**	**± 6.5**	**-0.7 ± 3.4**	**± 5.7**
	Lumbar range	NoLBP	24.1 ± 4.7	23.9 ± 4.3	23.3 ± 4.6	-23.8 ± 4.5	2.7±1.8	± 3.0	-0.2 ± 3.3	± 5.5	-0.2 ± 3.9	± 6.6
		LBP	24.3 ± 5.3	24.6 ± 5.9	23.1 ± 5.9	-24.1 ± 5.7	2.6±1.8	± 3.0	0.3 ± 3.5	± 5.8	-1.1 ± 3.2	± 5.3
	Pelvic angle	NoLBP	7.3 ± 4.1	7.1 ± 3.8	6.9 ± 3.6	-7.4 ± 3.8	2.1±1.7	± 2.8	-0.2 ± 2.5	± 4.2	-0.5 ± 2.7	± 4.5
		LBP	5.7 ± 2.8	6.8 ± 3.7	5.5 ± 3.5	-6.0 ± 3.4	1.5±1.2	± 2.0	1.1 ± 2.6	± 4.3	0.3 ± 2.4	± 4.1
Right lateral flexion†	**Trunk angle**	NoLBP	**31.9 ± 6.0**	**32.4 ± 6.5**	**31.6 ± 6.5**	**32 ± 6.2**	**2.9±1.6**	**± 2.6**	**-0.5 ± 2.9**	**± 4.9**	**-0.2 ± 2.7**	**± 4.5**
		LBP	**29.5 ± 5.1**	**29.8 ± 5.1**	**26.5 ± 5.7**	**28.8 ± 5.4**	**3.1±1.7**	**± 2.8**	**-0.3 ± 4.0**	**± 6.6**	**-2.6 ± 3.5**	**± 5.8**
	Lumbar range	NoLBP	24.4± 4.6	24.9 ± 4.5	24.7 ± 4.6	24.7 ± 4.5	2.2±1.4	± 2.3	-0.5 ± 2.4	± 4.0	-0.7 ± 3.1	± 5.2
		LBP	23.2 ± 5.2	22.8 ± 4.6	21.3 ± 5.7	22.3 ± 5.6	2.3±1.4	± 2.3	0.4 ± 3.0	± 5.1	1.9 ± 2.6	± 4.3
	Pelvic angle	NoLBP	7.7 ± 3.9	7.7 ± 4.0	7.1 ± 3.8	7.5 ± 3.9	1.9±1.3	± 2.1	0.0 ± 2.5	± 4.1	0.6 ± 2.7	± 4.5
		LBP	6.4 ± 2.9	7.1 ± 3.3	5.4 ± 3.3	6.4 ± 3.2	1.9±1.7	± 2.8	-0.7 ± 3.1	± 5.1	0.7 ± 2.8	± 4.8
Lumbo-pelvic rhythm		NoLBP	**51.9 % ± 9.6 %**	**50.0 % ± 9.0 %**	**52.0 % ± 9.6 %**	**51.3 % ± 9.4 %**	**3.6 % ± 2.2 %**	**± 3.6%**	**1.9 % ± 5.5 %**	**± 9.1 %**	**0.8 % ± 7.0 %**	**11.5 %**
		LBP	**45.4 % ± 8.9 %**	**45.6 % ± 8.6 %**	**46.4 % ± 10.7 %**	**45.8 % ± 8.6 %**	**3.3 % ± 2.0 %**	**± 3.3%**	**0.2 % ± 5.9 %**	**± 9.7 %**	**0.5 % ± 9.4 %**	**15.5 %**

Legend: LBP= LBP group, NoLBP= No LBP group, ROM= ROM

* ROM and standard deviation data represent the **group** mean and standard deviation (SD). The standard deviation indicates the magnitude of differences between individuals within the group

** These data are derived from the difference in ROM between tests for **each individual**, (i.e. Test 1 versus 2, Test 1 versus 3) then calculating group mean and SD of the difference scores.

† See Table 4 for numbers (n) of participants in each group

‡ Indicates significant difference between groups

9.14. Appendix N: Lumbar 'classifier' questionnaire

Only question 1 was used to provide a score for pain on bending, and question 11 and 12 for pain on sitting.

Low Back Pain - Aggravating activities and classifier

Pt Name:_____

Date:_____

Please read each question (1-12) and place a cross in the box for the response which best describes your lower back pain. There should be a cross in section A and a cross in section B for each question (for Q 1-8).

	Section A						Section B				TOTAL
(*Please answer all questions)	0	1	2	3	4		0	1	2	3	(A x B)
	(tick one box only in Section A)						(tick one box only in Section B)				
	Never	Rarely	Sometimes	Often	Always		None	Low	Medium	High	
1. Is your pain aggravated by bending forward activities?	☐	☐	☐	☐	☐	If so, is the level of increase:	☐	☐	☐	☐	____
2. Is your pain aggravated by putting socks & shoes on?	☐	☐	☐	☐	☐	If so, is the level of increase:	☐	☐	☐	☐	____
3. Is your pain eased by sitting upright or sitting with back support?	☐	☐	☐	☐	☐	If so, is the level of reduction of pain:	☐	☐	☐	☐	____
4. Is your pain eased by arching backward?	☐	☐	☐	☐	☐	If so, is the level of reduction of pain:	☐	☐	☐	☐	____

Sub Total Flexion ☐

5. Is your pain aggravated by standing for > 30minutes?	☐	☐	☐	☐	☐	If so, is the level of increase:	☐	☐	☐	☐	____
6. Would your low back pain increase with arching back activities? (eg: hanging clothes on line, changing a light globe)	☐	☐	☐	☐	☐	If so, is the level of increase:	☐	☐	☐	☐	____
7. Is your pain eased by bending or leaning forward?	☐	☐	☐	☐	☐	If so, is the level of reduction of pain:	☐	☐	☐	☐	____
8. Does sitting down ease your pain?	☐	☐	☐	☐	☐	If so, is the level of reduction of pain:	☐	☐	☐	☐	____

Sub Total Extension ☐

9. How long can you walk before your pain makes you want to stop?
<5 min ☐ 10 min ☐ 20 min ☐ 30 min ☐ 1 hour ☐ >2 hours ☐   Doesn't aggravate ☐

10. If pain stops you from walking any longer, what is your pain level (out of 10, when 10 is the worst possible pain)? ☐ (or "NA" if not applicable)

11. How long can you sit before you feel you need to stand up?
<5 min ☐ 10 min ☐ 20 min ☐ 30 min ☐ 1 hour ☐ >2 hours ☐   Doesn't aggravate ☐

12. If pain stops you from sitting any longer, what is your pain level (out of 10, when 10 is the worst possible pain)? ☐ (or "NA" if not applicable)

20130524

9.15. Appendix O: Description and details of measured lumbo-pelvic kinematics (Laird et al. 2018A)

Each participant was fitted with the wireless motion and surface EMG sensors as described in the method section. The initial calibration of lordosis was calculated by the absolute angular inclination against a vertical line determined by gravity. The sensors were then calibrated to 'zero' so that all movements started from a zeroed position. Integrity of motion and EMG was tested by performing a single practice movement of flexion while the clinician observed the output on the computer screen.

Description	Movement characteristics recorded	Details and instructions
Flexion ROM, three repetitions	Angular inclination of trunk (at T12) in degrees Angular inclination of pelvis (at S2) in degrees Lumbar spine ROM (T12 angle minus S2 angle) Lumbar contribution to flexion (%)* Flexion relaxation response (calculated as a ratio of sEMG activity – see Figure 2) Delay (lag) of pelvic versus lumbar timing at the start Delay (lag) of pelvic versus lumbar at 20o of movement Duration of bending motion	"Move from neutral standing to full flexion (towards your toes), at your own speed, hold for 3 seconds, then return to neutral" The time count of 3 seconds was provided. Each person had a test run of a single movement to ensure accurate calibration i.e. the sensors returned to a zeroed position. Data were then captured for three repetitions of flexion.
Usual sitting position (15 seconds with 5 seconds of captured data)	Trunk angle and pelvic angle Lumbar ROM (Angular inclination at T12 minus angular inclination at S2) 'Usual' sitting position calculated as a percentage where full posterior tilt = 100% and full upright sitting = 0%	No instructions, people were asked to sit on a 55cm or 65 cm ball (hips slightly higher than knees) while the assessor "worked on the computer" for 10 seconds to allow for a stable position to be established with minimal change, then 5 seconds of data captured).
Upright sitting position	Trunk angle and pelvic angle Lumbar ROM (Angular inclination at T12 minus angular inclination at S2)	The participant was asked to "sit upright as much as possible" for 10 seconds, then 5 seconds of data captured).

Slumped sitting position	Trunk angle and pelvic angle Lumbar ROM (Angular inclination at T12 minus angular inclination at S2)	The participant was asked to "sit in their tired, slumped, relaxed position" for 10 seconds, then 5 seconds of data captured).

9.16. Appendix P: Definition of kinematic characteristics for Laird et al. 2018B

Range of motion (ROM)

Trunk ROM was measured as angular inclination of the trunk at T12, pelvic ROM was measured as angular inclination of the pelvis at S2 and lumbar ROM was calculated using the difference between the angular inclinations at T12 and **S2.**

Lumbo-pelvic Coordination (rhythm)

Lumbo-pelvic coordination, sometimes described as lumbo-pelvic rhythm, is a method of describing lumbar versus pelvic contributions to movement. We calculated the relative contribution of lumbar movement at the end range of trunk flexion by using lumbar peak angle divided by trunk peak angle and expressed as a percentage.

Flexion relaxation response

A common pattern of thoraco-lumbar extensor muscle activity measured by surface electromyography (sEMG) is seen in people without back pain with electrical activity occurring at the start of trunk flexion (eccentric activation) and again on return from the fully flexed position (concentric activity), with minimal or no activity in the fully flexed position. This has been described as the flexion relaxation response (Floyd, W et al., 1951). Flexion relaxation is often absent in people with LBP when compared to people without LBP, and when restored, is associated with improvements in pain and activity limitation (Geisser, ME et al., 2005; Neblett, R et al., 2014a). It is possible that higher extensor muscle activity in the fully flexed position, a position that is recognised as a biomechanically vulnerable position for the intervertebral disc (O'Connell, GD et al., 2011), increases compressive loading. The flexion relaxation response was calculated as the sum of sEMG activity (millivolts) during 3 seconds in the fully flexed position (numerator) divided by the summed sEMG activity during both the eccentric (forward bending) and concentric (returning to upright stance) phases of flexion (denominator). The 'normal' complete muscle relaxation in full flexion would result in this flexion relaxation response being reported as close to or equal to zero. As muscle activity in end of range flexion increases, this ratio increases, with a

larger number indicating greater muscle activation in the fully flexed position. Figure 1 displays a person moving into flexion with the X axis representing time and the Y axis representing ROM. The green line indicates EMG activity of lumbar extensors muscles. The calculation for determining the flexion relaxation ratio is displayed.

Figure 1

Flexion relaxation ratio = $\dfrac{1}{2 + 3}$

Trunk ROM

Pelvic ROM

Lumbar ROM

= EMG activity of lumbar extensor muscles
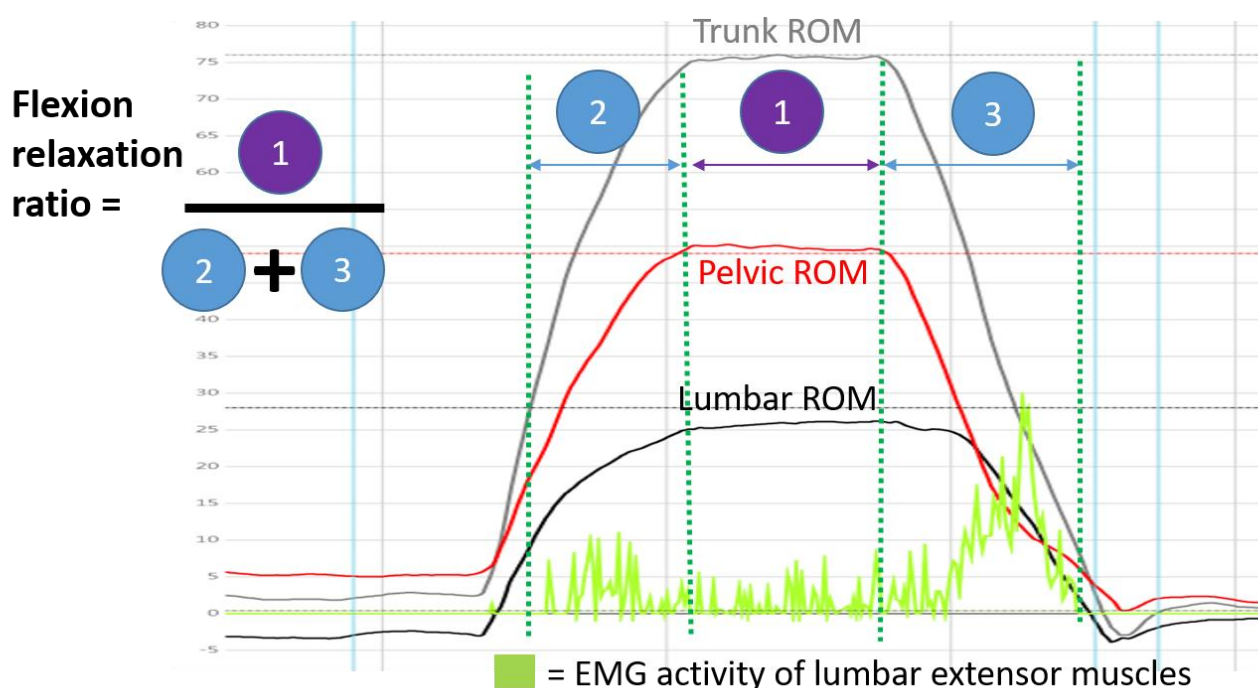
'Onset delay' and 'Delay-at-20°' of trunk flexion

Because motion sensors measure movement over time, it is possible to assess time-related synchronicity of lumbar versus pelvic contributions to flexion movement. There is evidence of time-related differences in lumbar versus pelvic movement during flexion (Wong, TK et al., 2004). An 'onset-delay' parameter measures which region, lumbar or pelvis, moves first and the time 'gap' between regions. Negative numbers indicate a delay in pelvic motion, with movement initiated first in the lumbar spine, while positive numbers indicate a delay in lumbar motion, with movement initiated at the pelvis. Larger numbers indicate a longer delay. The start of flexion was defined as the point at which velocity was > 7°/sec (the velocity required before movement was visible graphically). Figure 2 demonstrates an example of an onset-delay in pelvic movement. The 'delay-at 20°' parameter provides a similar view of movement discrepancy and is a calculation of the time needed to achieve 20° of angular inclination from the start of movement, for each region. Both parameters provide a measure of time-related synchronicity (or lack thereof) of lumbar versus pelvic contribution to flexion. The time difference in lumbar versus pelvic movement achieving 20° of angular inclination was chosen as almost all

333

participants produced a reading of 20° for both lumbar and pelvic movement, whereas at 30° and 40°, 13% and 33% of participants respectively did not achieve these angles for either lumbar or pelvic motion.

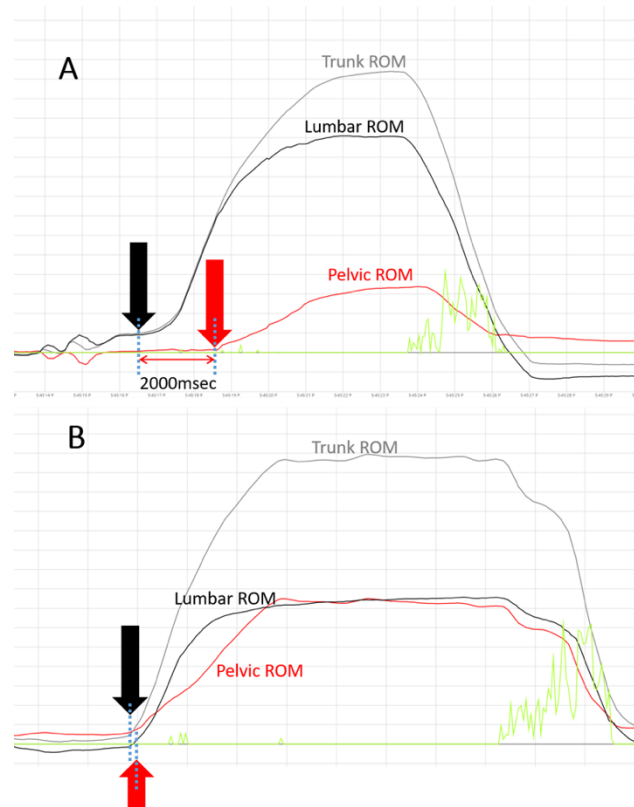**Figure 2: Onset delay of lumbar or pelvic movement**

Figure 2: These graphs show ROM (Y axis) changes over time (X axis). Graph A was from a person who moved their lumbar spine into flexion with a 2-second delay before the pelvis started moving. Graph B shows a more typical pattern with a synchronous start of movement of the lumbar spine and pelvis. The green line indicates EMG activity of lumbar extensor muscles.

Flexion movement duration

Flexion movement duration was defined as the time taken from start of trunk flexion (when velocity of movement was >7°/sec) to the fully flexed position (when velocity was <7°/sec velocity). We defined end of trunk flexion in this way because movement with a velocity less than 7°/sec is very close to end-range and this threshold minimises error that can result from the peak angle slowly increasing due to creep when the fully flexed position is sustained for the 3-second period during which we assessed the flexion relaxation response.

334

Sitting: Pelvic tilt range and pelvic tilt ratio

Pelvic tilt ROM (from full posterior to anterior tilt angular inclination) may be of clinical interest when sitting is associated with pain. Reduced pelvic repositioning accuracy (proprioception) and reduced movement variability have been identified in people with chronic LBP (Abboud, J et al., 2014; Hodges, PW et al., 2013; Laird, R et al., 2014; Seay, JF et al., 2011; Villumsen, M et al., 2016). The pelvic tilt range was measured by calculating the angular inclination of the pelvis between full anterior and full posterior tilt, which provided estimates of lower lumbar movement. The pelvic tilt ratio is a measure of the independence of pelvic tilt relative to trunk movement and is calculated by dividing the angular inclination of the pelvic sensor by the angular inclination of the trunk sensor. This parameter was used to test how pelvic tilting was performed i.e. whether movement was independently performed only in the lower lumbar motion or combined with upper lumbar motion, as might occur if a person simultaneously moved the trunk into flexion while performing posterior pelvic tilt). A number > 1 indicates larger pelvic than trunk ROM; a number <1 indicates larger trunk than pelvic ROM during the pelvic tilt manoeuvre.

Sitting: relative position

Measurements were made of usual, fully slumped (kyphotic) and fully upright (lordotic) sitting lumbar positions. The relative sitting position was calculated for usual sitting by deeming the fully slumped sitting position to be 100% and the fully upright sitting to be 0%. For example, if full slump was at 50° of lumbar flexion and full upright sitting was at 0° lumbar flexion, then the difference (50°-0°=50°) between maximum slump and upright sitting would represent 100% of the available ROM. If usual sitting was 25°, the relative sitting position would have been coded as 50%. This index enabled comparisons between individuals for defining usual sitting position relative to the available range of pelvic movement.

Bibliography

Asenlof, P., et al. (2005). "Individually tailored treatment targeting activity, motor behavior, and cognition reduces pain-related disability: A randomized controlled trial in patients with musculoskeletal pain." Journal of Pain **6**(9): 588-603.
> This study compares the outcomes of an individually tailored behavioral medicine intervention (experimental) with physical exercise therapy (control). The experimental intervention was systematically individualized according to each participant's behavioral treatment goals and functional behavioral analyses. One hundred twenty-two patients seeking care at 3 primary health care clinics because of musculoskeletal pain were randomized. Ninety-seven completed the trial. Data were collected at baseline, immediately after treatment, and at a 3-month follow-

up. Analyses of data from completers, as well as intention-to-treat analyses, showed that the experimental group experienced lower levels of disability (P = .01), lower maximum pain intensity (P = .02), higher levels of pain control (P = .001), and lower fear of movement (P = .022) as a result of treatment condition. Self-efficacy (P = .0001) and physical performance (P = .0001) increased over time for both groups. Participants in the experimental group generally reported more positive effects after treatment. Treatment fidelity was maintained during the course of the study. Activity can be resumed and pain might be managed by the patients themselves if treatment incorporates the biopsychosocial explanatory model of pain and strategies are tailored according to individual's priorities of everyday life activities and empirically derived determinants of pain-related disability. Perspective: This study shows that the biomedical and the psychosocial perspectives of the experiences and consequences of pain complement rather than contradict each other. Primary health care patients with persistent musculoskeletal pain benefit more from a systematic tailoring of treatments according to biopsychosocial factors than from a physically based exercise intervention. (c) 2005 by the American Pain Society.

Fersum, K. V., et al. (2012). "Efficacy of classification-based cognitive functional therapy in patients with non-specific chronic low back pain: A randomized controlled trial." European Journal of Pain **17**(6): 916-928.

Background Non-specific chronic low back pain disorders have been proven resistant to change, and there is still a lack of clear evidence for one specific treatment intervention being superior to another. Methods This randomized controlled trial aimed to investigate the efficacy of a behavioural approach to management, classification-based cognitive functional therapy, compared with traditional manual therapy and exercise. Linear mixed models were used to estimate the group differences in treatment effects. Primary outcomes at 12-month follow-up were Oswestry Disability Index and pain intensity, measured with numeric rating scale. Inclusion criteria were as follows: age between 18 and 65 years, diagnosed with non-specific chronic low back pain for >3 months, localized pain from T12 to gluteal folds, provoked with postures, movement and activities. Oswestry Disability Index had to be >14% and pain intensity last 14 days >2/10. A total of 121 patients were randomized to either classification-based cognitive functional therapy group n=62) or manual therapy and exercise group (n>=59). Results The classification-based cognitive functional therapy group displayed significantly superior outcomes to the manual therapy and exercise group, both statistically (p<0.001) and clinically. For Oswestry Disability Index, the classification-based cognitive functional therapy group improved by 13.7 points, and the manual therapy and exercise group by 5.5 points. For pain intensity, the classification-based cognitive functional therapy improved by 3.2 points, and the manual therapy and exercise group by 1.5 points. Conclusions The classification-based cognitive functional therapy produced superior outcomes for non-specific chronic low back pain compared with traditional manual therapy and exercise.

Hahne, A. J. P. B. P., et al. (2017). "Who Benefits Most From Individualized Physiotherapy or Advice for Low Back Disorders? A Preplanned Effect Modifier Analysis of a Randomized Controlled Trial." Spine **42**(21): E1215-E1224.

Study Design. A preplanned effect modifier analysis of the Specific Treatment of Problems of the Spine randomized controlled trial., Objective. To identify characteristics associated with larger or smaller treatment effects in people with low back disorders undergoing either individualized physical therapy or guideline-based advice., Summary of Background Data. Identifying subgroups of people who attain a larger or smaller benefit from particular treatments has been identified as a high research priority for low back disorders., Methods. The trial involved 300 participants with low back pain and/or referred leg pain (>=6 wk, <=6 mo duration), who satisfied criteria to be classified into five subgroups (with 228 participants classified into three subgroups relating to disc-related disorders, and 64 classified into the zygapophyseal joint dysfunction subgroup). Participants were randomly allocated to receive either two sessions of guideline based advice (n = 144), or 10 sessions of individualized physical therapy targeting pathoanatomical, psychosocial, and neurophysiological factors (n = 156). Univariate and multivariate linear mixed models determined the interaction between treatment group and potential effect modifiers (defined a priori) for the primary outcomes of back pain, leg pain (0-

10 Numeric Rating Scale) and activity limitation (Oswestry Disability Index) over a 52-week follow-up., Results. Participants with higher levels of back pain, higher Orebro scores (indicative of higher risk of persistent pain) or longer duration of symptoms derived the largest benefits from individualized physical therapy relative to advice. Poorer coping also predicted larger benefits from individualized physical therapy in the univariate analysis., Conclusion. These findings suggest that people with low back disorders could be preferentially targeted for individualized physical therapy rather than advice if they have higher back pain levels, longer duration of symptoms, or higher Orebro scores., Level of Evidence: 2, Copyright (C) 2017 Wolters Kluwer Health, Inc. All rights reserved.

Kent, P., et al. (2015). "The effect of changing movement and posture using motion-sensor biofeedback, versus guidelines-based care, on the clinical outcomes of people with sub-acute or chronic low back pain-a multicentre, cluster-randomised, placebo-controlled, pilot trial." BMC Musculoskeletal Disorders(16): 131-150.

Background: The aims of this pilot trial were to (i) test the hypothesis that modifying patterns of painful lumbo-pelvic movement using motion-sensor biofeedback in people with low back pain would lead to reduced pain and activity limitation compared with guidelines-based care, and (ii) facilitate sample size calculations for a fully powered trial.

Methods: A multicentre (8 clinics), cluster-randomised, placebo-controlled pilot trial compared two groups of patients seeking medical or physiotherapy primary care for sub-acute and chronic back pain. It was powered for longitudinal analysis, but not for adjusted single-time point comparisons. The intervention group (n = 58) received modification of movement patterns augmented by motion-sensor movement biofeedback (ViMove, dorsaVi.com) plus guidelines-based medical or physiotherapy care. The control group (n = 54) received a placebo (wearing the motion-sensors without biofeedback) plus guidelines-based medical or physiotherapy care. Primary outcomes were self-reported pain intensity (VAS) and activity limitation (Roland Morris Disability Questionnaire (RMDQ), Patient Specific Functional Scale (PSFS)), all on 0–100 scales. Both groups received 6–8 treatment sessions.

Outcomes were measured seven times during 10-weeks of treatment and at 12, 26 and 52 week follow-up, with 17.0 % dropout. Patients were not informed of group allocation or the study hypothesis.

Results: Across one-year, there were significant between-group differences favouring the intervention group [generalized linear model coefficient (95 % CI): group effect RMDQ −7.1 (95 % CI–12.6;–1.6), PSFS −10.3 (−16.6; −3.9), QVAS −7.7 (−13.0; −2.4); and group by time effect differences (per 100 days) RMDQ −3.5 (−5.2; −2.2), PSFS −4.7 (−7.0; −2.5), QVAS −4.8 (−6.1; −3.5)], all $p < 0.001$. Risk ratios between groups of probability of improving by >30 % at 12-months = RMDQ 2.4 (95 % CI 1.5; 4.1), PSFS 2.5 (1.5; 4.0), QVAS 3.3 (1.8; 5.9). The only device-related side-effects involved transient skin irritation from tape used to mount motion sensors.

Conclusions: Individualised movement retraining using motion-sensor biofeedback resulted in significant and sustained improvements in pain and activity limitation that persisted after treatment finished. This pilot trial also refined the procedures and sample size requirements for a fully powered RCT.

9.17. Appendix Q: Additional subgroup data and differences with p values

Shapiro-Wilk W test for normal data

```
    Variable |     Obs        W         V         z      Prob>z
-------------+-----------------------------------------------------
         Age |     266    0.94487   10.560     5.501    0.00000
      Gender |     266    0.99790    0.403    -2.123    0.98313
  Pain_Score |     139    0.98267    1.889     1.437    0.07539
  FLAG_score |     139    0.98499    1.637     1.112    0.13300
        RMDQ* |    139    0.96150    4.198     3.239    0.00060
      Tr_ROM* |    264    0.97870    4.052     3.264    0.00055
      Lx_ROM |     264    0.98918    2.059     1.684    0.04605
   Pelvic ROM |    264    0.99586    0.788    -0.556    0.71103
          LPR |    264    0.99005    1.894     1.490    0.06811
        FRR** |    260    0.57280   80.201    10.221    0.00000
   TimeMaxFl** |  205    0.90287   14.806     6.209    0.00000
   Diff at 0o** |  205    0.55745   67.458     9.702    0.00000
   Diff at 20o**|  198    0.83493   24.411     7.348    0.00000
```

* Histograms suggest that Trunk ROM and RMDQ are close to normally distributed

** Histograms confirm that age, flexion-relaxation-ratio and time-to-maximum-flexion (skewed), and Diff at 0° and Diff at 20° (large outliers) are not normally distributed

LPR = lumbo-pelvic rhythm

FRR = flexion relaxation response

TimeMaxFl = Time to maximum flexion

Differences between subgroups with p values

Age: using Kruskal-Wallis test then Dunn's pairwise comparison (Bonferroni adjustment): 1v3 ($p=0.0297$)

Gender: no diff between subgroups

Pain score: no diff between subgroups

F aggravation pain score (FLAG): oneway ANOVA (followed pairwise mean comparisons with Bonferonni adjustment for multiple comparisons): 4v1 ($p<0.000$), 4v2 ($p=0.001$), 4v3 ($p=0.049$)

RMDQ: using Kruskal-Wallis test then Dunn's pairwise comparison (no adjustment): 1v3 (0.0139), 1v4 (0.0069) then with (Bonferroni adjustment): 1v4 (0.0416)

RMDQ: oneway ANOVA with Tukey adjustment: 1v4 (0.016), with Bonferroni adjustment 1v4 (0.019)

FRR: Kruskill-Wallis (followed by Dunn's test pairwise comparisons with Bonferroni adjustment): 1v2, 1v3, 1v4 all $p<0.0000$, 2v3 $p=0.0038$, 2v4 $p=0.0001$

Time to maximum flexion: Kruskill-Wallis (followed by Dunn's test pairwise comparisons with Bonferroni adjustment): 1v2 $p<0.000$, 1v3 $p=0.0017$, 1v4 $p=0.0001$

Diff at 0º: Kruskill-Wallis (followed by Dunn's test pairwise comparisons with Bonferroni adjustment): 1v2 p<0.000, 1v4 p<0.0000, 2v3 p<0.0000, ,3v4 p<0.0000

Diff at 20º: Kruskill-Wallis (followed by Dunn's test pairwise comparisons with Bonferroni adjustment): 1v2 p<0.000, 1v3 p=0.0004, 1v4 p<0.0000, 2v3 p<0.0000, ,3v4 p<0.0000

Legpain: Kruskill-Wallis (followed by Dunn's test pairwise comparisons with Bonferroni adjustment): 1v2 p<0.000, 1v4 p<0.0000, 2v4 p=0.0013, 3v4 p<0.0000

Trunk ROM: oneway ANOVA (followed pairwise mean comparisons with Bonferonni adjustment for multiple comparisons):

```
-----------------------------------------------------------------------------
             |                         Bonferroni          Bonferroni
 Tr_PeakA_Av |  Contrast   Std. Err.     t     P>|t|    [95% Conf. Interval]
-------------+---------------------------------------------------------------
        clu_ |
      2 vs 1 | -13.92362   2.131624    -6.53   0.000   -19.59075   -8.256485
      3 vs 1 | -21.84941   2.611736    -8.37   0.000   -28.79296   -14.90585
      4 vs 1 | -33.15232   3.582827    -9.25   0.000   -42.67761   -23.62703
      3 vs 2 | -7.925792    2.84834    -2.78   0.035   -15.49838   -.3532057
      4 vs 2 |  -19.2287   3.758793    -5.12   0.000   -29.22182    -9.23559
      4 vs 3 | -11.30291   4.050416    -2.79   0.034   -22.07133   -.5344898
```

Lumbar ROM: oneway ANOVA (followed pairwise mean comparisons with Bonferonni adjustment for multiple comparisons):

```
-----------------------------------------------------------------------------
             |                         Bonferroni          Bonferroni
 Lx_PeakA_Av |  Contrast   Std. Err.     t     P>|t|    [95% Conf. Interval]
-------------+---------------------------------------------------------------
        clu_ |
      2 vs 1 |  2.807932   1.408592     1.99   0.284   -.9369459     6.55281
      3 vs 1 | -20.94059   1.725853   -12.13   0.000   -25.52894   -16.35224
      4 vs 1 | -4.849864   2.367557    -2.05   0.249   -11.14424    1.444514
      3 vs 2 | -23.74852   1.882202   -12.62   0.000   -28.75254   -18.74451
      4 vs 2 | -7.657796   2.483836    -3.08   0.014   -14.26131   -1.054279
      4 vs 3 |  16.09073   2.676542     6.01   0.000    8.974881    23.20657
-----------------------------------------------------------------------------
```

Pelvic ROM: oneway ANOVA (followed pairwise mean comparisons with Bonferonni adjustment for multiple comparisons):

```
-----------------------------------------------------------------------------
             |                         Bonferroni          Bonferroni
 Pe_PeakA_Av |  Contrast   Std. Err.     t     P>|t|    [95% Conf. Interval]
-------------+---------------------------------------------------------------
        clu_ |
      2 vs 1 | -16.54626    1.87468    -8.83   0.000   -21.53028   -11.56224
      3 vs 1 | -1.233861   2.296919    -0.54   1.000   -7.340444    4.872721
```

```
 4 vs 1  |  -29.23685   3.150956    -9.28   0.000   -37.61397   -20.85973
 3 vs 2  |    15.3124   2.505003     6.11   0.000    8.652603    21.97219
 4 vs 2  |  -12.69059    3.30571    -3.84   0.001   -21.47914   -3.902042
 4 vs 3  |  -28.00299   3.562181    -7.86   0.000   -37.47339   -18.53258
--------------------------------------------------------------------------
```

LPR_PercLx_PeakA: oneway ANOVA (followed pairwise mean comparisons with Bonferonni adjustment for multiple comparisons):

```
--------------------------------------------------------------------------
              |                         Bonferroni        Bonferroni
LPR_PercLx~A  |  Contrast   Std. Err.     t    P>|t|    [95% Conf. Interval]
--------------+-----------------------------------------------------------
        clu_  |
    2 vs 1    |   10.21241    1.22817     8.32   0.000    6.947206    13.47762
    3 vs 1    |  -11.94043   1.504794    -7.93   0.000   -15.94107   -7.939792
    4 vs 1    |   13.25892   2.064304     6.42   0.000    7.770765    18.74707
    3 vs 2    |  -22.15285   1.641117   -13.50   0.000   -26.51591   -17.78978
    4 vs 2    |   3.046502   2.165689     1.41   0.964   -2.711192    8.804196
    4 vs 3    |   25.19935   2.333712    10.80   0.000    18.99495    31.40375
--------------------------------------------------------------------------
```

10.   References (for entire thesis)

Abboud, J., Nougarou, F., Page, I., Cantin, V., Massicote, D., & Descarreaux, M. (2014). Trunk motor variability in patients with non-specific chronic low back pain. *European Journal of Applied Physiology*.

Adams, M. A., Bogduk, N., Burton, K., & Dolan, P. (2012). *The biomechanics of back pain* (3rd ed.). Edinburgh: Churchill Livingston.

Adams, M. A., Mannion, A. F., & Dolan, P. (1999). Personal risk factors for first-time low back pain. *Spine, 24*(23), 2497-2505.

Adams, N. (2006). Psychological, Electromyographic, and Neurochemical Aspects of Chronic Low Back Pain: Can a Biopsychosocial Model Be Confirmed? *J Musculoskel Pain, 14*(2), 33-44.

Ahern, D. K., Follick, M. J., Council, J. R., Laser-Wolston, N., & Litchman, H. (1988). Comparison of lumbar paravertebral EMG patterns in chronic low back pain patients and non-patient controls. *Pain, 34*(2), 153-160.

AIHW. (2016). *Impacts of chronic back problems*. (Bulletin 137, Cat. no. AUS 204). Canberra.

Akbari, A., Khorashadizadeh, S., & Abdi, G. (2008b). The effect of motor control exercise versus general exercise on lumbar local stabilizing muscles thickness: randomized controlled trial of patients with chronic low back pain. *Journal of Back & Musculoskeletal Rehabilitation, 21*(2), 105-112.

Aleksiev, A., Pope, M. H., Hooper, D. M., Wilder, D., Magnusson, M., Goel, V. K., et al. (1996). Pelvic unlevelness in chronic low back pain patients - Biomechanics and EMG time-frequency analyses. *European Journal of Medicine and Rehabilitation, 6*(1), 3-16.

Ali, A. A. (2002). *Management of the first episode of acute low back pain: a comparison between two treatment protocols.* (Ph.D.), Texas Woman's University. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=jlh&AN=2003095074&site=ehost-live Available from EBSCOhost jlh database.

Alschuler, K. N., Neblett, R., Wiggert, E., Haig, A. J., Geisser, M. E., Alschuler, K. N., et al. (2009). Flexion-relaxation and clinical features associated with chronic low back pain: A comparison of different methods of quantifying flexion-relaxation. *Clinical Journal of Pain, 25*(9), 760-766.

Aluko, A., DeSouza, L., & Peacock, J. (2011). Evaluation of trunk acceleration in healthy individuals and those with low back pain. *International Journal of Therapy and Rehabilitation, 18*(1), 18-25.

Amonoo-Kuofi, H. (1992). Changes in the lumbosacral angle, sacral inclination and the curvature of the lumbar spine during aging. *Acta Antatomica, 145*, 373-377.

Arun, R. D. M. M., Freeman, B. J. C. D. M. F., Scammell, B. E. D. M. F., McNally, D. S. P., Cox, E. P., & Gowland, P. P. (2009). 2009 ISSLS Prize Winner: What Influence Does Sustained Mechanical Load Have on Diffusion in the Human Intervertebral Disc?: An In Vivo Study Using Serial Postcontrast Magnetic Resonance Imaging. *Spine, 34*(21), 2324-2337.

Astfalck, R. G., O'Sullivan, P. B., Straker, L. M., Smith, A. J., Burnett, A., Caneiro, J. P., et al. (2010). Sitting postures and trunk muscle activity in adolescents with and without nonspecific chronic low back pain: an analysis based on subclassification. *Spine, 35*(14), 1387-1395.

Bacher, J., Wenzig, K., & Vogler, M. (2004). SPSS TwoStep Cluster – a first evaluation. 23. Retrieved from http://nbn-resolving.de/urn:nbn:de:0168-ssoar-327153 website:

Bakhtiary, A. H., Safavi-Farokhi, Z., & Rezasoltani, A. (2005). Lumbar stabilizing exercises improve activities of daily living in patients with lumbar disc herniation. *Journal of Back and Musculoskeletal Rehabilitation, 18*(3-4), 55-60.

Barrett, C. J., Singer, K. P., & Day, R. (1999). Assessment of combined movements of the lumbar spine in asymptomatic and low back pain subjects using a three-dimensional electromagnetic tracking system. *Manual Therapy, 4*(2), 94-99.

Bartholdy, C., Juhl, C., Christensen, R., Lund, H., Zhang, W., & Henriksen, M. (2017). The role of muscle strengthening in exercise therapy for knee osteoarthritis: A systematic review and meta-regression analysis of randomized trials. *Seminars in Arthritis & Rheumatism, 47*(1), 9-21.

Battié, M. C., Videman, T., Kaprio, J., Gibbons, L. E., Gill, K., Manninen, H., et al. (2009). The Twin Spine Study: Contributions to a changing view of disc degeneration. *The Spine Journal, 9*(1), 47-59.

Bauer, C. M., Baumgartner, L., Schelldorfer, S., Ernst, M., & Lawrence, M. (2012). Technical validation of a new movement therapy system for treatment of low back pain. *Gait & Posture, 36*, S40.

Bauer, C. M., Rast, F. M., Ernst, M. J., Kool, J., Oetiker, S., Rissanen, S. M., et al. (2015). Concurrent validity and reliability of a novel wireless inertial measurement system to assess trunk movement. *Journal of Electromyography and Kinesiology, 25*(5), 782-790.

Beckwee, D., Degelaen, M., Eggermont, M., Gonzalez-Rodriguez, M., Lefeber, N., Vaes, P., et al. (2016). Validity and test-retest reliability of the Stride Analyzer in people with knee osteoarthritis. *Gait & Posture, 49*, 155-158.

Been, E., & Kalichman, L. (2014). Lumbar lordosis. *Spine Journal: Official Journal of the North American Spine Society, 14*(1), 87-97.

Ben Salah Frih, Z., Fendri, Y., Jellad, A., Boudoukhane, S., & Rejeb, N. (2009). Efficacy and treatment compliance of a home-based rehabilitation programme for chronic low back pain: a randomized, controlled study. *Annals of Physical & Rehabilitation Medicine, 52*(6), 485-496.

Berger-Roscher, N., Casaroli, G., Rasche, V., Villa, T., Galbusera, & Wilke, H. J. (2016). Influence of complex loading conditions on intervertebral disc failure. *Spine, 42*(2), E78-E85.

Bhattacharya, A., Biely, S., & Silfies, S. P. (2009). Qualitative analysis of lumbopelvic movement patterns in individuals with mechanical low back pain: a kinematic study. *Journal of Orthopaedic & Sports Physical Therapy, 39*(1), A84-85.

Bible, J. E., Simpson, A. K., Emerson, J. W., Biswas, D., & Grauer, J. N. (2008). Quantifying the effects of degeneration and other patient factors on lumbar segmental range of motion using multivariate analysis. *Spine, 33*(16), 1793-1799.

Biering-Sorensen, F. (1984a). A one-year prospective study of low back trouble in a general population. The prognostic value of low back history and physical measurements. *Danish Medical Bulletin, 31*(5), 362-375.

Biering-Sorensen, F. (1984b). Physical measurements as risk indicators for low-back trouble over a one-year period. *Spine, 9*(2), 106-119.

Boline, P., Keating, J., Haas, M., & Anderson, A. (1992). Interexaminer reliability and discriminant validity of inclinometric measurement of lumbar rotation in chronic low-back pain patients and subjects without low-back pain. *Spine, 17*(3), 335-338.

Borkan, J. M. M. D. P., Koes, B. P., Reis, S. M. D., & Cherkin, D. C. P. (1998). A Report From the Second International Forum for Primary Care Research on Low Back Pain: Reexamining Priorities. *Spine, 23*(18), 1992-1996.

Bossuyt, P. M., Reitsma, J. B., Bruns, D. E., Gatsonis, C. A., Glatsonis, P. P., Irwig, L. M., et al. (2003). Towards complete and accurate reporting of studies of diagnostic accuracy: The STARD Initiative. *Radiology, 226*, 24-28.

Boston, J. R., Rudy, T. E., Lieber, S. J., & Stacey, B. R. (1995). Measuring treatment effects on repetitive lifting for patients with chronic low back pain: speed, style, and coordination. *Journal of Spinal Disorders, 8*(5), 342-351.

Briffa, T., Majorana, A., Sheerin, N., Stubbs, A., Oldenburg, B., Sammel, N., et al. (2006). Physical activity for people with cardiovascular disease: recommendations of the National Heart Foundation of Australia. *Medical journal of Australia, 184*(2), 71-75.

Britt, H., Miller, G., Henderson, J., Bayram, C., Harrison, C., Valenti, L., et al. (2016). *General practice activity in Australia 2015–16* General practice series no. 40.,

Brody, K., Nasypany, A. M., Baker, R. T., & May, J. M. (2017). Analysis of Patient Outcomes Using the MyoKinesthetic System for the Treatment of Low Back Pain: A Case Series. *Journal of Chiropractic Medicine, 16*(2), 111-121.

Brox, J. I., Sorensen, R., Friis, A., Nygaard, O., Indahl, A., Keller, A., et al. (2003). Randomized clinical trial of lumbar instrumented fusion and cognitive intervention and exercises in patients with chronic low back pain and disc degeneration. *Spine, 28*(17), 1913-1921.

Brumagne, S., Cordo, P., Lysens, R., Verschueren, S., & Swinnen, S. (2000). The role of paraspinal muscle spindles in lumbosacral position sense in individuals with and without low back pain. *Spine, 25*(8), 989-994.

Brumagne, S., Lysens, R., & Spaepen, A. (1999). Lumbosacral repositioning accuracy in standing posture: a combined electrogoniometric and videographic evaluation. *Clinical Biomechanics, 14*(5), 361-363.

Bryan, M., & Hawson, S. (2003). The Benefits of Pilates Exercise in Orthopaedic Rehabilitation. *Techniques in Orthopaedics March, 18*(1), 126-129.

Bunzli, S., Smith, A., Watkins, R., Schutze, R., & O'Sullivan, P. (2015). What Do People Who Score Highly on the Tampa Scale of Kinesiophobia Really Believe?: A Mixed Methods Investigation in People With Chronic Nonspecific Low Back Pain. *Clinical Journal of Pain, 31*(7), 621-632.

Bystrom, M. G., Rasmussen-Barr, E., & Grooten, W. J. A. (2013). Motor Control Exercises Reduces Pain and Disability in Chronic and Recurrent Low Back Pain A Meta-Analysis. *Spine, 38*(6), E350-E358.

Caneiro, J. P., Smith, A., Rabey, M. M. M. T., Moseley, L., & O'Sullivan, P. (2017). Process of change in pain-related fear: Clinical insights from a single case report of persistent back pain managed with cognitive functional therapy. *Journal of Orthopaedic & Sports Physical Therapy, 47*(9), 637-651.

Carroll, L. J., Cassidy, J. D., & Cote, P. (2004). Depression as a risk factor for onset of an episode of troublesome neck and low back pain. *Pain, 107*(1-2), 134-139.

Castanharo, R., Duarte, M., & McGill, S. (2014). Corrective sitting strategies: An examination of muscle activity and spine loading. *Journal of Electromyography and Kinesiology, 24*(1), 114-119.

Castelein, B., Cools, A., Parlevliet, T., & Cagnie, B. (2017). The influence of induced shoulder muscle pain on rotator cuff and scapulothoracic muscle activity during elevation of the arm. *Journal of Shoulder & Elbow Surgery, 26*(3), 497-505.

Celestini, M., Marchese, A., Serenelli, A., & Graziani, G. (2005). A randomized controlled trial on the efficacy of physical exercise in patients braced for instability of the lumbar spine. *Europa Medicophysica, 41*(3), 223-231.

Charry, E., Umer, M., & Taylor, S. (2011). Design and validation of an ambulatory inertial system for 3-D measurements of low back movements. *Proceedings of Seventh International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP 2011) IEEE Conference Publications (http://ieeexplore.ieee.org/document/6146618/)*.

Chen, S. P., Samo, D. G., Chen, E. H., Crampton, A. R., Conrad, K. M., Egan, L., et al. (1997). Reliability of three lumbar sagittal motion measurement methods: surface inclinometers. *Journal of Occupational & Environmental Medicine, 39*(3), 217-223.

Chien CW, B. K., Khan A, et al. (2013). Comparative responsiveness of verbal and numerical rating scales to measure pain intensity in patients with chronic pain. *Journal of Pain, 14*, 1653-1662.

Childs, J., Piva, S., & Erhard, R. (2004). Immediate improvements in side-to-side weight bearing and iliac crest symmetry after manipulation in patients with low back pain. *Journal of Manipulative and Physiological Therapeutics, 27*(5), 306-313.

Christie, H. J., Kumar, S., & Warren, S. A. (1995). Postural aberrations in low back pain. *Archives of Physical Medicine and Rehabilitation, 76*(3), 218-224.

Claeys, K., Brumagne, S., Dankaerts, W., Kiers, H., & Janssens, L. (2011). Decreased variability in postural control strategies in young people with non-specific low back pain is associated with altered proprioceptive reweighting. *European Journal of Applied Physiology, 111*(1), 115-123.

Claus, A. P., Hides, J. A., Moseley, G. L., & Hodges, P. W. (2009). Is 'ideal' sitting posture real? Measurement of spinal curves in four sitting postures. *Manual Therapy, 14*(4), 404-408.

Claus, A. P., Hides, J. A., Moseley, G. L., & Hodges, P. W. (2016). Thoracic and lumbar posture behaviour in sitting tasks and standing: Progressing the biomechanics from observations to measurements. *Applied Ergonomics, 53*, 161-168.

Claus, A. P., Hides, J. A., Moseley, G. L., & Hodges, P. W. (2018). Different ways to balance the spine in sitting: Muscle activity in specific postures differs between individuals with and without a history of back pain in sitting. *Clinical Biomechanics, 52*, 25-32.

Coenen, P., Kingma, I., Boot, C., Twisk, J., Bongers, P., & Dieën, J. (2013). Cumulative Low Back Load at Work as a Risk Factor of Low Back Pain: A Prospective Cohort Study. *Journal of Occupational Rehabilitation, 23*(1), 11-18.

Collins, L., & Lanza, S. (2010). *Latent class and latent transition analysis with applications in the social, behavioral, and health sciences.* (Vol. 2010). Hoboken: John Wiley & Sons, Inc.

Costa, L., Koes, B., Pransky, G., Borkan, J., Maher, C., & Smeets, R. (2013). Primary Care Research Priorities in Low Back Pain: An Update. *Spine, 38*(2), 148-156.

Croft, P., Papageorgiou, A., Thomas, E., Macfarlane, G., & Silman, A. (1999). Short-Term Physical Risk Factors for New Episodes of Low Back Pain: Prospective Evidence From the South Manchester Back Pain Study. *Spine, 24*, 1556.

Crombez, G., Vlaeyen, J. W., Heuts, P. H., & Lysens, R. (1999). Pain-related fear is more disabling than pain itself: evidence on the role of pain-related fear in chronic back pain disability. *Pain, 80*(1-2), 329-339.

Crosbie, J., de Faria Negrao Filho, R., Nascimento, D. P., & Ferreira, P. (2013). Coordination of spinal motion in the transverse and frontal planes during walking in people with and without recurrent low back pain. *Spine, 38*(5), E286-292.

Curnow, D., Cobbin, D., Wyndham, J., & Choy, S. T. B. (2009). Altered motor control, posture and the Pilates method of exercise prescription. *Journal of Bodywork & Movement Therapies, 13*(1), 104-111.

da Fonseca, J. L., Magini, M., & de Freitas, T. H. (2009). Laboratory gait analysis in patients with low back pain before and after a pilates intervention. *Journal of Sport Rehabilitation, 18*(2), 269-282.

Dankaerts, W., O'Sullivan, P., Burnett, A., & Straker, L. (2006). Altered patterns of superficial trunk muscle activation during sitting in nonspecific chronic low back pain patients: importance of subclassification. *Spine, 31*(17), 2017-2023.

Dankaerts, W., O'Sullivan, P., Burnett, A., & Straker, L. (2006a). Differences in sitting postures are associated with nonspecific chronic low back pain disorders when patients are subclassified. *Spine, 31*(6), 698-704.

Dankaerts, W., O'Sullivan, P., Burnett, A., Straker, L., Davey, P., & Gupta, R. (2009). Discriminating healthy controls and two clinical subgroups of nonspecific chronic low back pain patients using trunk muscle activation and lumbosacral kinematics of postures and movements: A statistical classification model. *Spine, 34*(15), 1610-1618.

Dankaerts, W., O'Sullivan, P. B., Burnett, A. F., & Straker, L. M. (2007). The use of a mechanism-based classification system to evaluate and direct management of a patient with non-specific chronic low back pain and motor control impairment--a case report. *Manual Therapy, 12*(2), 181-191.

Dankaerts, W., O'Sullivan, P. B., Straker, L. M., Burnett, A. F., & Skouen, J. S. (2006d). The inter-examiner reliability of a classification method for non-specific chronic low back pain patients with motor control impairment. *Manual Therapy, 11*(1), 28-39.

Danneels, L., Vanderstraeten, G., Cambier, D., Witvrouw, E., Bourgois, J., Dankaerts, W., et al. (2001). Effects of three different training modalities on the cross sectional area of the lumbar multifidus muscle in patients with chronic low back pain. *British Journal of Sports Medicine, 35*(3), 186-191.

Day, J. W., Smidt, G. L., & Lehmann, T. (1984). Effect of pelvic tilt on standing posture. *Physical Therapy, 64*(4), 510-516.

de Fonseca, J. L., Magini, M., & de Freitas, T. H. (2009). Laboratory gait analysis in patients with low back pain before and after a Pilates intervention. *Journal of Sport Rehabilitation, 18*(2), 269-282.

de Morton, N. (2009). The PEDro scale is a valid measure of the methodological quality of clinical trials: a demographic study. *Australian Journal of Physiotherapy, 55*(2), 192-133.

Delitto, A., Erhard, R. E., & Bowling, R. W. (1995). A treatment-based classification approach to low back syndrome: identifying and staging patients for conservative treatment... including

commentary by DeRosa CP and Greathouse DG with author response. *Physical Therapy, 75*(6), 470-489.

Demoulin, C., Maquet, D., Tomasella, M., Croisier, J.-L., Crielaard, J.-M., & Vanderthommen, M. (2006). Benefits of a Physical Training Program After Back School for Chronic Low Back Pain Patients. *Journal of Musculoskeletal Pain, 14*(2), 21-31.

Derman, K. L., Derman, E. W., & Noakes, T. D. (1995). A lumbar body support (KBS 2000) alters lumbar muscle recruitment patterns in patients with acute-upon-chronic lower back pain. *South African Medical Journal, 85*(4), 278-282.

Descarreaux, M., Blouin, J.-S., & Teasdale, N. (2005a). Isometric force production parameters during normal and experimental low back pain conditions. *BMC Musculoskeletal Disorders, 6*, 6.

Descarreaux, M., Blouin, J.-S., & Teasdale, N. (2005b). Repositioning accuracy and movement parameters in low back pain subjects and healthy control subjects. *European Spine Journal, 14*(2), 185-191.

Deyo, R., Bryan, M., Comstock, B., Turner, J., Heagerty, P., Friedly, J., et al. (2015). Trajectories of Symptoms and Function in Older Adults With Low Back Disorders. *Spine, 40*(17), 1352-1362.

Dijk, M., Smorenberg, N., Visser, B., Heerkens, Y., & Nijhuis-van der Sanden, M. (2017). How clinicians analyze movement quality in patients with non-specific low back pain: a cross-sectional survey study with Dutch allied health care professionals. *BMC Musculoskeletal Disorders, 18*(288), 1-11.

Dionne, C. E., Dunn, K. M., Croft, P. R., Nachemson, A. L., Buchbinder, R., Walker, B. F., et al. (2008). A consensus approach toward the standardization of back pain definitions for use in prevalence studies. *Spine, 33*(1), 95-103.

Dopf, C. A., Mandel, S. S., Geiger, D. F., & Mayer, P. J. (1994). Analysis of spine motion variability using a computerized goniometer compared to physical examination. *Spine, 19*(5), 586-595.

Dubois, J., Piche, M., Cantin, V., & Descarreaux, M. (2011). Effect of experimental low back pain on neuromuscular control of the trunk in healthy volunteers and patients with chronic low back pain. *Journal of Electromyography & Kinesiology, 21*(5), 774-781.

Dunk, N. M., & Callaghan, J. P. (2010). Lumbar spine movement patterns during prolonged sitting differentiate low back pain developers from matched asymptomatic controls. *Work, 35*(1), 3-14.

Dworkin, R. H., Turk, D. C., Wyrwich, K. W., Beaton, D., Cleeland, C. S., Farrar, J. T., et al. (2008). Interpreting the Clinical Importance of Treatment Outcomes in Chronic Pain Clinical Trials: IMMPACT Recommendations. *The Journal of Pain, 9*(2), 105-121.

Dwornik, M., Kujawa, J., Bialoszewski, D., Slupik, A., & Kiebzak, W. (2009). Electromyographic and clinical evaluation of the efficacy of neuromobilization in patients with low back pain. *Ortopedia Traumatologia Rehabilitacja, 11*(2), 164-176.

Elnaggar, I. M. (1991). The effects of spinal flexion and extension exercises on low back pain severity and spinal mobility in chronic mechanical low back pain1888. *Spine, 16*(8), 967-972.

Engel, G. L. (1977). The need for a new medical model: A challange for biomedicine. *Science, 196*(4286), 129-136.

Ernst, E., & Canter, P. H. (2003). The Alexander technique: a systematic review of controlled clinical trials. *Forschende Komplementarmedizin und Klassische Naturheilkunde, 10*(6), 325-329.

Esola, M. A., McClure, P. W., Fitzgerald, G. K., & Siegler, S. (1996). Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain. *Spine, 21*(1), 71-78.

Ferreira, M. L., Ferreira, P. H., Latimer, J., Herbert, R. D., Hodges, P. W., Jennings, M. D., et al. (2007). Comparison of general exercise, motor control exercise and spinal manipulative therapy for chronic low back pain: A randomized trial. *Pain, 131*(1-2), 31-37.

Ferreira, P., Ferreira, M., Maher, C., Herbert, R., & Refshauge, K. (2006). Specific stabilisation exercise for spinal and pelvic pain: A systematic review. *Australian Journal of Physiotherapy, 52*, 79-88.

Ferreira, P., Ferreira, M., Maher, C., Refshauge, K., Herbert, R., & Hodges, P. (2010). Changes in recruitment of transversus abdominis correlate with disability in people with chronic low back pain. *British Journal of Sports Medicine, 44*, 1166-1172.

Ferreira, P. H., Ferreira, M. L., & Hodges, P. W. (2004). Changes in recruitment of the abdominal muscles in people with low back pain ultrasound measurement of muscle activity. *Spine, 29*(2), 2560–2566.

Fersum, K. V., O'Sullivan, P., Skouen, J. S., Smith, A., & Kvale, A. (2012). Efficacy of classification-based cognitive functional therapy in patients with non-specific chronic low back pain: A randomized controlled trial. *European Journal of Pain, 17*(6), 916-928.

Field, E., Abdel-Moty, E., & Loudon, J. (1997). The effect of back injury and load on ability to replicate a novel posture. *Journal of Back and Musculoskeletal Rehabilitation, 8*(3), 199-207.

Fitzgerald, G., Wynveen, K., Rheault, W., & Rothschild, B. (1983). Objective assessment with establishment of normal values for lumbar spinal range of motion. *Physical Therapy, 63*(11), 1776-1781.

Floyd, W., & Silver, P. (1951). The function of the erectores spinae muscles in flexion of the trunk. *Lancet, 6647*, 123-133.

Ford, J. J., Hahne, A. J., Surkitt, L. D., Chan, A. Y., Richards, M. C., Slater, S. L., et al. (2016). Individualised physiotherapy as an adjunct to guideline-based advice for low back disorders in primary care: a randomised controlled trial. *British Journal of Sports Medicine, 50*(4), 237-245.

Freeman, M. D., Woodham, M. A., & Woodham, A. W. (2010). The role of the lumbar multifidus in chronic low back pain: a review. *Pm & R, 2*(2), 142-146; quiz 141 p following 167.

Fritz, J., Delitto, A., & Erhard, R. (2003). Comparison of Classification-Based Physical Therapy With Therapy Based on Clinical Practice Guidelines for Patients with Acute Low Back Pain: A Randomized Clinical Trial. *Spine, 28*(13), 1363-1371.

Fritz, J. M., Cleland, J. A., & Childs, J. D. (2007). Subgrouping patients with low back pain: Evolution of a classification approach to physical therapy. *Journal of Orthopaedic & Sports Physical Therapy, 37*(6), 290-302.

Froud, R., Patterson, S., Eldridge, S., Seale, C., Pincus, T., Rajendran, D., et al. (2014). A systematic review and meta-synthesis of the impact of low back pain on people's lives. *BMC Musculoskeletal Disorders, 15*, 50-64.

Gallagher, S., Marras, W. S., Litsky, A. S., Burr, D., Gallagher, S., Marras, W. S., et al. (2005). Torso flexion loads and the fatigue failure of human lumbosacral motion segments. *Spine, 30*(20), 2265-2273.

Geisser, M. E., Haig, A. J., Wallbom, A. S., Wiggert, E. A., Geisser, M. E., Haig, A. J., et al. (2004). Pain-related fear, lumbar flexion, and dynamic EMG among persons with chronic musculoskeletal low back pain. *Clinical Journal of Pain, 20*(2), 61-69.

Geisser, M. E., Ranavaya, M., Haig, A. J., Roth, R. S., Zucker, R., Ambroz, C., et al. (2005). A meta-analytic review of surface electromyography among persons with low back pain and normal, healthy controls. *Journal of Pain, 6*(11), 711-726.

Gelb, D., Lenke, L., Bridwell, K., Blanke, K., & McEnery, K. (1995). An Analysis of Sagittal Spinal Alignment in 100 Asymptomatic Middle and Older Aged Volunteers. *Spine, 20*(12), 1351-1358.

Gelbard, R., Goldman, O., & Spiegler, I. (2007). Investigating diversity of clustering methods: An empirical comparison. *Data & Knowledge Engineering, 63*, 155-166.

Georgy, E. (2011a). Lumbar repositioning accuracy as a measure of proprioception in patients with back dysfunction and healthy controls. *Asian Spine Journal, 5*(4).

Georgy, E. (2011b). Lumbar repositioning accuracy as a measure of proprioception in patients with back dysfunction and healthy controls. *Asian Spine Journal, 5*(4), 201-207.

Giggins, O. M., Persson, U. M., & Caulfield, B. (2013). Biofeedback in rehabilitation. *Journal of NeuroEngineering and Rehabilitation, 10*(1).

Gill, K., & Callaghan, M. (1998). The measurement of lumbar proprioception in individuals with and without low back pain. *Spine, 23*(3), 371-377.

Godwin, A., Agnew, M., & Stevenson, J. (2009). Accuracy of inertial motion sensors in static, quasistatic, and complex dynamic motion. *Journal of Biomechanical Engineering, 131*(11), 114501.

Goldberg, M. S., Scott, S. C., & Mayo, N. E. (2000). A review of the association between cigarette smoking and the development of nonspecific back pain and related outcomes. *Spine, 25*(8), 995-1014.

Goldby, L. J., Moore, A. P., Doust, J., & Trew, M. E. (2006). A randomized controlled trial investigating the efficiency of musculoskeletal physiotherapy on chronic low back disorder. *Spine, 31*(10), 1083-1093.

Gombatto, S., D'Arpa, N., Landerholm, S., Mateo, C., O'Connor, R., Tokunaga, J., et al. (2017). Difference in kinematics of the lumbar spine and lower extremities between people with and without low back pain during the down phase of a pick up task, an observational study. *Musculoskeletal Science and Practice, 28*, 25-31.

Gombatto, S. P., Collins, D. R., Sahrmann, S. A., Engsberg, J. R., & Van Dillen, L. R. (2007). Patterns of lumbar region movement during trunk lateral bending in 2 subgroups of people with low back pain. *Physical Therapy, 87*(4), 441-454.

Gomez, T. T. (1994). Symmetry of lumbar rotation and lateral flexion range of motion and isometric strength in subjects with and without low back pain. *Journal of Orthopaedic and Sports Physical Therapy, 19*(1), 42-48.

Govindu, N. K., & Babski-Reeves, K. (2014). Effects of personal, psychosocial and occupational factors on low back pain severity in workers. *International Journal of Industrial Ergonomics, 44*(2), 335-341.

Gray, A. D., Willis, B. W., Skubic, M., Huo, Z., Razu, S., Sherman, S. L., et al. (2017). Development and Validation of a Portable and Inexpensive Tool to Measure the Drop Vertical Jump Using the Microsoft Kinect V2. *Sports & Health, 9*(6), 537-544.

Gregory, D. E., Callaghan, J. P., Gregory, D. E., & Callaghan, J. P. (2008). Prolonged standing as a precursor for the development of low back discomfort: an investigation of possible mechanisms. *Gait & Posture, 28*(1), 86-92.

Grenier, S. G., & McGill, S. M. (2008). When exposed to challenged ventilation, those with a history of LBP increase spine stability relatively more than healthy individuals. *Clin. Biomech., 23*(9), 1105-1111.

Grimstone, S. K., & Hodges, P. W. (2003). Impaired postural compensation for respiration in people with recurrent low back pain. *Experimental Brain Research, 151*(2), 218-224.

Ha, T. H., Saber-Sheikh, K., Moore, A. P., & Jones, M. P. (2012). Measurement of lumbar spine range of movement and coupled motion using inertial sensors - A protocol validity study. *Manual Therapy*.

Hahne, A. J., Keating, J. L., & Wilson, S. C. (2004). Do within-session changes in pain intensity and range of motion predict between-session changes in patients with low back pain? *Australian Journal of Physiotherapy, 50*(1), 17-23.

Haldeman, S., Kopansky-Giles, D., Hurwitz, E. L., Hoy, D., Mark Erwin, W., Dagenais, S., et al. (2012). Advancements in the management of spine disorders. *Best Practice & Research in Clinical Rheumatology, 26*(2), 263-280.

Hamaoui, A., Do, M., Poupard, L., Bouisset, S., & Do, M. c. (2002). Does respiration perturb body balance more in chronic low back pain subjects than in healthy subjects? *Clinical Biomechanics, 17*(7), 548-550.

Hamberg-van Reenen, H. H., Ariens, G. A. M., Blatter, B. M., van Mechelen, W., & Bongers, P. M. (2007). A systematic review of the relation between physical capacity and future low back and neck/shoulder pain. *Pain, 130*(1-2), 93-107.

Hancock, M. J., & Hill, J. C. (2016). Are small effects for back pain interventions really surprising? *Journal of Orthopaedic & Sports Physical Therapy, 46*(5), 317-319.

Harris-Hayes, M., Van Dillen, L. R., Harris-Hayes, M., & Van Dillen, L. R. (2009). The inter-tester reliability of physical therapists classifying low back pain problems based on the movement system impairment classification system. *Pm & R, 1*(2), 117-126.

Harrison, D., Cailliet, R., Harrison, D., Janik, T., & Holland, B. (2002). Changes in sagittal lumbar configuration with a new method of extension traction: nonrandomized clinical controlled trial. *Archives of Physical Medicine and Rehabilitation, 83*(11), 1585-1591.

Harrison, D. E., Cailliet, R., Betz, J. W., Harrison, D. D., Colloca, C. J., Haas, J. W., et al. (2005). A non-randomized clinical control trial of Harrison mirror image methods for correcting trunk list (lateral translations of the thoracic cage) in patients with chronic low back pain. *European Spine Journal, 14*(2), 155-162.

Hartvigsen, J., Hancock, M. J., Kongsted, A., Louw, Q., Ferreira, M. L., Genevay, S., et al. (2018). What low back pain is and why we need to pay attention. *The Lancet*.

Hauggaard, A., & Persson, A. L. (2007). Specific spinal stabilisation exercises in patients with low back pain -- a systematic review. *Physical Therapy Reviews, 12*(3), 233-248.

Haugstad, G., Haugstad, T., Kirste, U., Leganger, S., Hammel, B., Klemmetsen, I., et al. (2006a). Reliability and validity of a standardized Mensendieck physiotherapy test (SMT). *Physiotherapy Theory and Practice, 22*(4), 189-205.

Haugstad, G., Haugstad, T., Kirste, U., Leganger, S., Wojniusz, S., Klemmetsen, I., et al. (2006b). Posture, movement patterns, and body awareness in women with chronic pelvic pain. *Journal of Psychosomatic Research, 61*(5), 637-644.

Haugstad, G. K., Haugstad, T. S., Kirste, U. M., Leganger, S., Klemmetsen, I., Malt, U. F., et al. (2006). Mensendieck somatocognitive therapy as treatment approach to chronic pelvic pain: results of a randomized controlled intervention study. *American Journal of Obstetrics & Gynecology, 194*(5), 1303-1310.

Haugstad, G. K., Haugstad, T. S., Kirste, U. M., Leganger, S., Wojniusz, S., Klemmetsen, I., et al. (2008). Continuing improvement of chronic pelvic pain in women after short-term Mensendieck somatocognitive therapy: results of a 1-year follow-up study. *American Journal of Obstetrics and Gynecology, 199*(6), 615.e611-618.

Hayden, J., van Tulder, M., Malmivaara, A., & Koes, B. (2011). Exercise therapy for treatment of non-specific low back pain. *Cochrane Database of Systematic Reviews*(3).

Heeswijk, V., Thambyah, A., Robert, P., & Broom , N. (2017). Posterolateral disc prolapse in flexion initiated by lateral inner annular failure. *Spine, 42*(21), 1604-1613.

Hemming, R., Sheeran, L., van Deursen, R., & Sparkes, V. (2017). Non-specific chronic low back pain: differences in spinal kinematics in subgroups during functional tasks. *European Spine Journal, 27*(1), 163-170.

Henry, S. M., Fritz, J. M., Trombley, A. R., & Bunn, J. Y. (2012). Reliability of a Treatment-Based Classification System for Subgrouping People With Low Back Pain. *Journal of Orthopaedic & Sports Physical Therapy, 42*(9), 797-805.

Henschke, N., Maher, C., Refshauge, K., Herbert, R., Cumming, R., Bleasel, J., et al. (2009). Characteristics of Patients With Acute Low Back Pain Presenting to Primary Care in Australia. *Clinical Journal of Pain, 25*(1), 5-11.

Hestbaek, L., Leboeuf, C., & Manniche, C. (2003). Low back pain: what is the long-term course? A review of studies of general patient populations. *European Spine Journal, 12*(2), 149-165.

Hidalgo, B., Gilliaux, M., Poncin, W., & Detrembleur, C. (2012). Reliability and validity of a kinematic spine model during active trunk movement in healthy subjects and patients with chronic non-specific low back pain. *Journal of Rehabilitation Medicine, 44*(9), 756-763.

Hidalgo, B., Gobert, F., Bragard, D., & Detrembleur, C. (2013). Effects of proprioceptive disruption on lumbar spine repositioning error in a trunk forward bending task. *Journal of Back & Musculoskeletal Rehabilitation, 26*(4), 381-387.

Hides, J., Gilmore, C., Stanton, W., & Bohlscheid, E. (2008). Multifidus size and symmetry among chronic LBP and healthy asymptomatic subjects. *Manual Therapy, 13*(1), 43-49.

Hides, J., Richardson, C., & Jull, G. (1996). Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain. *Spine, 21*(23), 2763-2769.

Hides, J. A., Jull, G. A., & Richardson, C. A. (2001). Long-term effects of specific stabilizing exercises for first-episode low back pain. *Spine, 26*(11), E243-248.

Higgins, J., & Green, S. (2011). *Cochrane Handbook for Systematic Reviews of Interventions, Version 5.1.0*

Higgins, J., Thompson, S., Deeks, J., & Altman, D. G. (2003). Measuring inconsistency in meta-analyses. *British Medical Journal (Clinical Research Ed.), 327*(9), 557-560.

Hodges, P., Cholewicki, J., & Van Dieen, J. (2013). *Spinal Control: the rehabilitation of back pain* (P. Hodges, J. Cholewicki, & J. Van Dieen Eds.). Edinburgh: Elsevier.

Hodges, P., & Richardson, C. (1996). Inefficient muscular stabilization of the lumbar spine associated with low back pain: a motor control evaluation of transversus abdominus. *Spine, 21*(22), 2640-2650.

Hodges, P., van den Horn, W., Dawson, A., & Cholewicki, J. (2009). Changes in the mechanical properties of the trunk in low back pain may be associated with recurrence. *Journal of Biomechanics, 42*(1), 61-66.

Hodges, P. W. (2003). Core stability exercise in chronic low back pain. *Orthopedic Clinics of North America, 34*(2), 245-254.

Hodges, P. W., Coppieters, M. W., MacDonald, D., & Cholewicki, J. (2013). New insight into motor adaptation to pain revealed by a combination of modelling and empirical approaches. *European Journal of Pain, 17*(8), 1138-1146.

Hoffman, S. L., Johnson, M. B., Zou, D., Harris-Hayes, M., & Van Dillen, L. R. (2011). Effect of classification-specific treatment on lumbopelvic motion during hip rotation in people with low back pain. *Manual Therapy, 16*(4), 344-350.

Hollingworth, W., Medina, S., Lenkinski, R., Shibata, D., Bernal, B., Zurakowski, D., et al. (2006). Interrater reliability in assessing quality of diagnostic accuracy studies using the QUADAS tool. *Academic Radiology, 13*(7), 803-810.

Hoy, D., Brooks, P., Blyth, F., & Buchbinder, R. (2010). The Epidemiology of low back pain. *Best Practice & Research Clinical Rheumatology, 24*, 769-781.

Huber, J., Lisinski, P., Samborski, W., & Wytrazek, M. (2011). The effect of early isometric exercises on clinical and neurophysiological parameters in patients with sciatica: An interventional randomized single-blinded study. *Isokinetics and Exercise Science, 19*(3), 207-214.

Hultman, G., Nordin, M., Saraste, H., & Ohlsen, H. (1993). Body composition, endurance, strength, corss-sectional area, and desnity of MM erector spinae in men with and without low back pain. *Journal of Spinal Disorders, 6*, 114-123.

Ikeda, K., & McGill, S. (2012). Can altering motions, postures, and loads provide immediate low back pain relief: A study of 4 cases investigating spine load, posture, and stability. *Spine, 37*(23), E1469-1475.

Iles, R. A., Davidson, M., & Taylor, N. F. (2008). Psychosocial predictors of failure to return to work in non-chronic non-specific low back pain: A systematic review. *Occupational and Environmental Medicine, 65*(8), 507-517.

Indahl, A., Velund, L., & Reikeraas, O. (1995). Good prognosis for low back pain when left untampered: A randomized clinical trial. *Spine, 20*(4), 473-477.

Intolo, P., Milosavljevic, S., Baxter, D. G., Carman, A. B., Pal, P., Munn, J., et al. (2009). The effect of age on lumbar range of motion: a systematic review. *Manual Therapy, 14*(6), 596-604.

Iversen, M. D., Kale, M. K., & Sullivan, J. T., Jr. (2009). Pilot case control study of postural sway and balance performance in aging adults with degenerative lumbar spinal stenosis. *Journal of Geriatric Physical Therapy, 32*(1), 15-21.

Jacobs, J. V., Henry, S. M., Jones, S. L., Hitt, J. R., & Bunn, J. Y. (2011). A history of low back pain associates with altered electromyographic activation patterns in response to perturbations of standing balance. *Journal of Neurophysiology, 106*(5), 2506-2514.

Jacobs, J. V., Henry, S. M., & Nagle, K. J. (2009). People With Chronic Low Back Pain Exhibit Decreased Variability in the Timing of Their Anticipatory Postural Adjustments. *Behavioral Neuroscience, 123*(2), 455-458.

Jain, S., Janssen, K., DeCelle, S., Jain, S., Janssen, K., & DeCelle, S. (2005). Alexander technique and Feldenkrais method: a critical overview. *Physical Medicine & Rehabilitation Clinics of North America, 15*(4), 811-825.

Johannsen, F., Remvig, L., Kryger, P., Beck, P., Warming, S., Lybeck, K., et al. (1995). Exercises for chronic low back pain: a clinical trial. *Journal of Orthopaedic & Sports Physical Therapy, 22*(2), 52-59.

Kaila-Kangas, L., Leino-Arjas, P., Riihimaki, H., Luukkonen, R., & Kirjonen, J. (2003). Smoking and overweight as predictors of hospitalization for back disorders. *Spine, 28*(16), 1860-1868.

Karayannis, N., Jull, G., & Hodges, P. (2012). Physiotherapy movement based classification approaches to low back pain: comparison of subgroups through review and developer/expert survey. *BMC Musculoskeletal Disorders, 13*(24).

Karimi, N., Ebrahimi, I., Ezzati, K., Kahrizi, S., Torkaman, G., & Arab, A. M. (2009). The effects of consecutive supervised stability training on postural balance in patients with chronic low back pain. *Pakistan Journal of Medical Sciences, 25*(2), 177-181.

Kato, K., Sekiguchi, M., Nikaido, T., Otoshi, K., Matsuo, Y., Igari, T., et al. (2017). Psychosocial Stress After a Disaster and Low Back Pain-Related Interference With Daily Living Among College Students: A Cohort Study in Fukushima. *Spine, 42*(16), 1255-1260.

Kawaguchi, M., Matsudaira, K., Sawada, T., Koga, T., Ishizuka, A., Isomura, T., et al. (2017). Assessment of potential risk factors for new onset disabling low back pain in Japanese workers: findings from the CUPID (cultural and psychosocial influences on disability) study. *BMC Musculoskeletal Disorders, 18*(1), 334.

Kell, R. T., Bhambhani, Y., Kell, R. T., & Bhambhani, Y. (2006). In vivo erector spinae muscle blood volume and oxygenation measures during repetitive incremental lifting and lowering in chronic low back pain participants. *Spine, 31*(22), 2630-2637.

Kendall, F., McCreary, E., Provance, P., Rodgers, M., & Romani, W. (2005). *Muscles: Testing and Function, with Posture and Pain* (5th ed.). Baltimore: Lippincott Williams & Wilkins.

Kent, P., & Keating, J. (2004). Do Primary-Care Clinicians Think That Nonspecific Low Back Pain Is One Condition? *Spine, 29*(9), 1022-1031.

Kent, P., & Keating, J. L. (2005). Classification in non-specific low back pain - what methods do primary care clinicians currently use? *Spine, 30*, 1434-1440.

Kent, P., Laird, R., & Haines, T. (2015a). The effect of changing movement and posture using motion-sensor biofeedback, versus guidelines-based care, on the clinical outcomes of people with sub-acute or chronic low back pain-a multicentre, cluster-randomised, placebo-controlled, pilot trial. *BMC Musculoskeletal Disorders*(16), 131-150.

Kent, P. M., Keating, J. L., & Taylor, N. F. (2009). Primary care clinicians use variable methods to assess acute nonspecific low back pain and usually focus on impairments. *Manual Therapy, 14*(1), 88-100.

Kent, P. P., & Lauridsen, H. H. P. (2011). Managing Missing Scores on the Roland Morris Disability Questionnaire. *Spine, 36*(22), 1878-1884.

Key, J. (2010). *Back pain: a movement problem*. Edinburgh: Churchill Livingstone Elsevier.

Khalil T, S, A., L, M., S, W., R, R., & H, R. (1992). Stretching in the rehabilitation of low-back pain patients. *Spine, 17*(3), 311-317.

Kilby, J., Heneghan, N. R., & Maybury, M. (2012). Manual palpation of lumbo-pelvic landmarks: A validity study. *Manual Therapy, 17*(3), 259-262.

Kim, M., Yi, C., Kwon, O., Cho, S., Cynn, H., Kim, Y., et al. (2013). Comparison of Lumbopelvic Rhythm and Flexion-Relaxation Response Between 2 Different Low Back Pain Subtypes. *Spine, 38*(15), 1260-1267.

Klaber Moffett J, & Frost, H. (2000). Back to fitness programme. The manual for phsyiotherapists to set up the classes. . *Physiotherapy, 86*, 295-305.

KNAW. (2018). Replication studies – Improving reproducibility in the empirical sciences. https://www.knaw.nl/shared/resources/actueel/publicaties/pdf/20180115-replication-studies-web

Koes, B., van Tulder, M., Chung-Wei, C., Macedo, L., McAuley, J., & Maher, C. (2010). An updated overview of clinical guidelines for the management of non-specific low back pain in primary care. *European Spine Journal, 19*, 2075-2094.

Koes, B., van Tulder, M., and Thomas, S. (2006). Diagnosis and treatment of low back pain. *British Medical Journal, 332*, 1430-1434.

Kofotolis, N., & Kellis, E. (2006). Effects of two 4-week proprioceptive neuromuscular facilitation programs on muscle endurance, flexibility, and functional performance in women with chronic low back pain. *Physical Therapy, 86*(7), 1001-1012.

Kolar, P., Sulc, J., Kyncl, M., Sanda, J., Cakrt, O., Andel, R., et al. (2012). Postural function of the diaphragm in persons with and without chronic low back pain. *Journal of Orthopaedic & Sports Physical Therapy, 42*(4), 352-362.

Kongsted, A., Kent, P., Albert, h., Jensen, T., & Manniche, C. (2012). Patients with low back pain differ from those who also have leg pain or signs of nerve root involvement – a cross-sectional study. *BMC Musculoskeletal Disorders, 12*, 236-245.

Kongsted, A., Kent, P., Hestbaek, L., & Vach, W. (2015). Patients with low back pain had distinct clinical course patterns that were typically neither complete recovery nor constant pain. A latent class analysis of longitudinal data. *The Spine Journal, 15*, 885-894.

Koopmans, L., Owen, D., & Rosenblatt, J. (1964). Confidence intervals for the coefficient of variation for the normal and log normal distributions. *Biometrika, 51*, 25-32.

Koppenhaver, S. L., Hebert, J. J., Parent, E. C., & Fritz, J. M. (2009). Rehabilitative ultrasound imaging is a valid measure of trunk muscle size and activation during most isometric sub-maximal contractions: a systematic review. *Australian Journal of Physiotherapy, 55*(3), 153-169.

Koumantakis, G. A., Watson, P. J., & Oldham, J. A. (2005). Trunk muscle stabilization training plus general exercise versus general exercise only: Randomized controlled trial of patients with recurrent low back pain. *Physical Therapy, 85*(3), 209-225.

Koumantakis, G. A., Winstanley, J., & Oldham, J. A. (2002). Thoracolumbar proprioception in individuals with and without low back pain: intratester reliability, clinical applicability, and validity. *Journal of Orthopaedic and Sports Physical Therapy, 32*(7), 327-335.

Kraemer, H., Wilson, G., Fairburn, C. G., & Agras, W. (2002). Mediators and moderators of treatment effects in randomized clinical trials. *Archives of General Psychiatry, 59*(10), 877-883.

Kratchochwill, T., Hitchcock, K., Horner, R., Levin, K., S, O., Rindskopf, d., et al. (2010). Single-case design technical documentation: Version 1.0 (Pilot). Retrieved from What Works Clearinghouse website: website: https://ies.ed.gov/ncee/wwc/Docs/ReferenceResources/wwc_scd.pdf

Kuo, C., Hu, H., Lin, R., Huang, K., Lin, P., Zhong, Z.., et al. (2010). Biomechanical analysis of the lumbar spine on facet joint force and intradiscal pressure--a finite element study. *BMC Musculoskeletal Disorders, 11*, 151.

Laird, R., Gilbert, J., Kent, P., & Keating, J. (2014). Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis. *BMC Musculoskeletal Disorders, 15*(1), 229.

Laird, R., Keating, J., & Kent, P. (2018B). There are subgroups of lumbo-pelvic flexion kinematics in people with and without back pain *BMC Musculoskeletal Disorders, Submitted*.

Laird, R., Kent, P., & Keating, J. (2012). Modifying patterns of movement in people with low back pain - does it help? A systematic review. *BMC Musculoskeletal Disorders, 13*, 169.

Laird, R., Kent, P., & Keating, J. (2016). How consistent are lordosis, range of movement and lumbo-pelvic rhythm in people with and without back pain? *BMC Musculoskeletal Disorders*(17), 403-417.

Laird, R., Kent, P., Li, P., Ussing, K., & Keating, J. (2018A). Does movement matter in people with back pain? Investigating 'atypical' lumbo-pelvic kinematics in people with and without back pain using wireless movement sensors. *BMC Musculoskeletal Disorders, submitted*.

Lalanne, K., Lafond, D., & Descarreaux, M. (2009). Modulation of the flexion-relaxation response by spinal manipulative therapy: a control group study. *Journal of Manipulative & Physiological Therapeutics, 32*(3), 203-209.

Lamberg, E. M., & Hagins, M. (2012). The effects of low back pain on natural breath control during a lowering task. *European Journal of Applied Physiology, 112*(10), 3519-3524.

Lamoth, C. J. C., Stins, J. F., Pont, M., Kerckhoff, F., & Beek, P. J. (2008). Effects of attention on the control of locomotion in individuals with chronic low back pain. *Journal of neuroengineering and rehabilitation, 5*.

Lariviere, C., Gagnon, D., & Loisel, P. (2000). The effect of load on the coordination of the trunk for subjects with and without chronic low back pain during flexion-extension and lateral bending tasks. *Clinical Biomechanics, 15*(6), 407-416.

Lee, A. S., Cholewicki, J., Reeves, N. P., Zazulak, B. T., & Mysliwiec, L. W. (2010). Comparison of Trunk Proprioception Between Patients With Low Back Pain and Healthy Controls. *Archives of Physical Medicine and Rehabilitation, 91*(9), 1327-1331.

Lee, H., Hubscher, M., Moseley, G. L., Kamper, S. J., Traeger, A. C., Mansell, G., et al. (2015). How does pain lead to disability? A systematic review and meta-analysis of mediation studies in people with back and neck pain. *Pain, 156*(6), 988-997.

Lee, H., Mansell, G., McAuley, J. H., Kamper, S. J., Hübscher, M., Moseley, G. L., et al. (2016). Causal mechanisms in the clinical course and treatment of back pain. *Best Practice & Research Clinical Rheumatology*.

Lee, J., Hoshino, Y., Nakamura, K., & Ooi, Y. (1999). Trunk muscle imbalance as a risk factor of the incidence of low back pain: a 5-year propsective [sic] study. *J Neuomusculoskeletal Syst, 7*(3), 97-101.

Lee, R. Y. W., & Wong, T. K. T. (2002). Relationship between the movements of the lumbar spine and hip. *Human Movement Science, 21*(4), 481-494.

Leinonen, V., Kankaanpaa, M., Airaksinen, O., & Hanninen, O. (2000). Back and hip extensor activities during trunk flexion/extension: effects of low back pain and rehabilitation. *Archives of Physical Medicine & Rehabilitation, 81*(1), 32-37.

Lewis, J. S., Hewitt, J. S., Billington, L., Cole, S., Byng, J., & Karayiannis, S. (2005). A randomized clinical trial comparing two physiotherapy interventions for chronic low back pain. *Spine, 30*(7), 711-721.

Liebenson, C. (2007). *Rehabilitation of the spine : a practitioner's manual* (2nd ed.). Baltimore: Lippincott Williams & Wilkins.

Lim, E. C. W., Poh, R. L. C., Low, A. Y., & Wong, W. P. (2011). Effects of Pilates-Based Exercises on Pain and Disability in Individuals With Persistent Nonspecific Low Back Pain: A Systematic Review With Meta-analysis. *Journal of Orthopaedic & Sports Physical Therapy, 41*(2), 70-80.

Little, P., Lewith, G., Webley, F., Evans, M., Beattie, A., Middleton, K., et al. (2008a). Randomised controlled trial of Alexander technique lessons, exercise, and massage (ATEAM) for chronic and recurrent back pain.[see comment]. *BMJ, 337*, a884.

Long, A., Donelson, R., & Fung, T. (2004). Does it matter which exercise? A randomized control trial of exercise for low back pain. *Spine, 29*(23), 2593-2602.

Lu, W. W., Luk, K. D., Cheung, K. M., Wong, Y. W., & Leong, J. C. (2001). Back muscle contraction patterns of patients with low back pain before and after rehabilitation treatment: an electromyographic evaluation. *J Spinal Disord, 14*(4), 277-282.

Luoto, S., Taimela, S., Alaranta, H., & Hurri, H. (1998). Psychomotor speed and postural control in chronic low-back pain patients and healthy controls - Determinants and predictive value for functional restoration outcome. *European Journal of Physical Medicine and Rehabilitation, 8*(3), 81-86.

Macedo, L. G., Maher, C. G., Latimer, J., & McAuley, J. H. (2009). Motor Control Exercise for Persistent, Nonspecific Low Back Pain: A Systematic Review. *Physical Therapy, 89*(1), 9-25.

Magidson, J., & Vermunt, J. (2002). Latent class models for clustering: A comparison with k-means. *Canadian Journal of Market Research, 20*, 1-9.

Magnusson, M. L., Chow, D. H., Diamandopoulos, Z., & Pope, M. H. (2008). Motor control learning in chronic low back pain. *Spine, 33*(16), E532-538.

Maher, C. G., Sherrington, C., Herbert, R. D., Moseley, A. M., & Elkins, A. (2003). Reliability of the PEDro scale for rating quality of randomized controlled trials. *Physical Therapy, 83*, 713-721.

Maitland, G. (1986). *Vertebral manipulation* (5th ed.). London, England: Butterworth-Heinemann.

Maitland, G. (1991). *Peripheral manipulation* (3rd ed.). London: Butterworth-Heinemann.

Manniche, C., Asmussen, K., Lauritsen, B., Vinterberg, H., Kreiner, S., & Jordan, A. (1994). Low Back Pain Rating scale: validation of a tool for assessment of low back pain. *Pain, 57*(3), 317-326.

Mannion, A., & Troke, M. (1999). A comparison of two motion analysis devices used in the measurement of lumbar spinal mobility. *Clinical Biomechanics, 14*(9), 612-619.

Mannion, A. F., Junge, A., Taimela, S., Muntener, M., Lorenzo, K., & Dvorak, J. (2001a). Active therapy for chronic low back pain: part 3. Factors influencing self-rated disability and its change following therapy. *Spine, 26*(8), 920-929.

Mannion, A. F., Muntener, M., Taimela, S., & Dvorak, J. (1999a). 1999 Volvo Award Winner in Clinical Studies: a randomized clinical trial of three active therapies for chronic low back pain. *Spine, 24*(23), 2435-2448.

Mannion, A. F., Taimela, S., Muntener, M., & Dvorak, J. (2001b). Active therapy for chronic low back pain part 1. Effects on back muscle activation, fatigability, and strength. *Spine, 26*(8), 897-908.

Mansell, G. M., Hill, J. C. P., Kamper, S. J. P., Kent, P. P., Main, C. P., & van der Windt, D. A. P. (2014). How Can We Design Low Back Pain Intervention Studies to Better Explain the Effects of Treatment? *Spine, 39*(5), E305-E310.

Maribo, T., Schiottz-Christensen, B., Jensen, L. D., Andersen, N. T., & Stengaard-Pedersen, K. (2012). Postural balance in low back pain patients: criterion-related validity of centre of pressure assessed on a portable force platform. *European spine journal : official publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society, 21*(3), 425-431.

Marin-Martines, F., & Sanchez-Meca, J. (1999). Averaging dependent effect sizes in meta-analysis: a coutionary note about procedures. *The Spanish Journal of Psychology, 2*(1), 32-38.

Marin, T. J., Van Eerd, D., Irvin, E., Couban, R., Koes, B. W., Malmivaara, A., et al. (2017). Multidisciplinary biopsychosocial rehabilitation for subacute low back pain. *Cochrane Database of Systematic Reviews*(6).

Marras, W., Ferguson, S., Burr, D., Schabo, P., & Maronitis, A. (2007). Low back pain recurrence in occupational environments. *Spine, 32*(21), 2387-2397.

Marras, W., Parnianpour, M., Ferguson, S., Kim, J., Crowell, R., Bose, S., et al. (1995). The classification of anatomic- and symptom-based low back disorders using motion measure models. *Spine, 20*(23), 2531-2546.

Marras, W. S., Ferguson, S. A., Gupta, P., Bose, S., Parnianpour, M., Kim, J. Y., et al. (1999a). The quantification of low back disorder using motion measures: Methodology and validation. *Spine, 24*(20), 2091-2100.

Marras, W. S., Parnianpour, M., Ferguson, S. A., & al, e. (1993a). Quantification and classification low back disorders based on trunk motion. *Eur J Phys Med, 3*, 218-235.

Marras, W. S., Parnianpour, M., Ferguson, S. A., Kim, J. Y., Crowell, R. R., & Simon, S. R. (1993b). Quantification and classification of low back disorders based on trunk motion. *European Journal of Physical Medicine & Rehabilitation, 3*(6), 218-235.

Marras, W. S., & Wongsam, P. E. (1986). Flexibility and velocity of the normal and impaired lumbar spine. *Archives of Physical Medicine & Rehabilitation, 67*(4), 213-217.

Marshall, P., & Murphy, B. (2006). Changes in the flexion relaxation response following an exercise intervention. *Spine, 31*(23), E877-883.

Marshall, P., & Murphy, B. (2008). Muscle activation changes after exercise rehabilitation for chronic low back pain. *Archives of Physical Medicine and Rehabilitation, 89*(7), 1305-1313.

Marshall, P., & Murphy, B. (2008). Self-report measures best explain changes in disability compared with physical measures after exercise rehabilitation for chronic low back pain. *Spine, 33*(3), 326-338.

Marshall, P. W., Desai, I., & Robbins, D. W. (2011). Core stability exercises in individuals with and without chronic nonspecific low back pain. *Journal of Strength & Conditioning Research, 25*(12), 3404-3411.

Martin, B. I., Deyo, R. A., Mirza, S. K., & et al. (2008). Expenditures and health status among adults with back and neck problems. *JAMA, 299*(6), 656-664.

May, S., & Aina, A. (2012). Centralization and directional preference: A systematic review. *Manual Therapy, 17*(6), 497-506.

May, S., & Johnson, R. (2008). Stabilisation exercises for low back pain: a systematic review. *Physiotherapy, 94*(3), 179-189.

Mayer, J., Mooney, V., & Dagenais, S. (2008). Evidence-informed management of chronic low back pain with lumbar extensor strengthening exercises. *Spine Journal, 8*(1), 96-113.

Mayer, T., Kondraske, G., Beals, S., & Gatchel, R. (1997). Spinal range of motion. Accuracy and sources of error with inclinometric measurement. *Spine, 22*, 1976-1984.

Mayer, T., Neblett, R., Brede, E., & Gatchel, R. (2009). The quantified lumbar flexion-relaxation phenomenon is a useful measurement of improvement in a functional restoration program. *Spine, 34*(22), 2458-2465.

Mayer, T., Tencer, A., Kristoferson, S., & Mooney, V. (1984). Use of noninvasive techniques for quantification of spinal range-of-motion in normal subjects and chronic low-back dysfunction patients. *Spine, 9*(6), 588-595.

McAlindon, T. E., Bannuru, R. R., Sullivan, M. C., Arden, N. K., Berenbaum, F., Bierma-Zeinstra, S. M., et al. (2014). OARSI guidelines for the non-surgical management of knee osteoarthritis. *Osteoarthritis and Cartilage, 22*(3), 363-388.

McClure, P., Esola, M., Schreier, R., & Siegler, S. (1997). Kinematic analysis of lumbar and hip motion while rising from a forward, flexed position in patients with and without a history of low back pain. *Spine, 22*(5), 552-558.

McGill, S. (2016) Low back disorders: evidence-based prevention and rehabilitation. Champaign, Illinois: Human Kinetics.

McGorry, R. W., & Lin, J.-H. (2012). Flexion relaxation and its relation to pain and function over the duration of a back pain episode. *PLoS ONE [Electronic Resource], 7*(6), e39207.

McGregor, A., McCarthy, I., Dore, C., & Hughes, S. (1997a). Quantitative assessment of the motion of the lumbar spine in the low back pain population and the effect of different spinal pathologies on this motion. *European Spine Journal, 6*(5), 308-315.

McGregor, A., McCarthy, I., & Hughes, S. (1995). Motion characteristics of the lumbar spine in the normal population. *Spine, 20*(22), 2421-2428.

McGregor, A., McCarthy, I., & Hughes, S. (1997b). Lumbar spine motion during freestyle lifting and changes in this motion with time. *Journal of Back and Musculoskeletal Rehabilitation, 9*(1), 35-37.

McGregor, A. H., & Hughes, S. P. (2000). The effect of test speed on the motion characteristics of the lumbar spine during an A-P flexion-extension test. *Journal of Back and Musculoskeletal Rehabilitation, 14*(3), 99-104.

McGregor, A. H., McCarthy, I. D., Dore, C. J., & Hughes, S. P. (1997). Quantitative assessment of the motion of the lumbar spine in the low back pain population and the effect of different spinal pathologies of this motion. *European Spine Journal, 6*(5), 308-315.

McGregor, A. H., McCarthy, I. D., & Hughes, S. P. F. (1995). Motion characteristics of normal subjects and people with low back pain. *Physiotherapy, 81*(10), 632-637.

McKenzie, R. (1987). Mechanical diagnosis and therapy for low back pain: Toward a better understanding. In L. Twomey & J. Taylor (Eds.), *Physical Therapy of the low back* (pp. 157-173). New York: Churchill Livingstone.

McKenzie, R., & May, S. (2003a). *Lumbar Spine, Mechanical Diagnosis and Therapy* (2nd ed.). Waikanae, New Zealand: Spinal Publications Ltd.

McLaughlin, L., Goldsmith, C. H., & Coleman, K. (2011). Breathing evaluation and retraining as an adjunct to manual therapy. *Manual Therapy, 16*(1), 51-52.

Mellin, G. (1990). Decreased joint and spinal mobility associated with low back pain in young adults. *Journal of Spinal Disorders, 3*(3), 238-243.

Mellin, G., Harkapaa, K., Vanharanta, H., Hupli, M., Heinonen, R., & Jarvikoski, A. (1993). Outcome of a multimodal treatment including intensive physical training of patients with chronic low back pain. *Spine, 18*(7), 825-829.

Merriaux, P., Dupuid, Y., Boutteau, R., Vasseur, P., & Savatier, X. (2017). A Study of Vicon System Positioning Performance. *Sensors, 17*, 1591-1608.

Meziat Filho, N., Coutinho, E. S., & Azevedo E Silva, G. (2015). Association between home posture habits and low back pain in high school adolescents. *European Spine Journal, 24*(3), 425-433.

Mielenz, T. J., Garrett, J. M., & Carey, T. S. (2008). Association of psychosocial work characteristics with low back pain outcomes. *Spine, 33*(11), 1270-1275.

Mieritz, R., Bronfort, G., Kawchuk, G., Breen, A., & Hartvigsen, J. (2012). Reliability and measurement error of 3-dimensional regional lumbar motion measures: a sytematic review. *Journal of Manipulative and Physiological Therapeutics, 35*(8), 645-656.

Miller, S. A., Mayer, T., Cox, R., & Gatchel, R. J. (1992). Reliability problems associated with the modified schober technique for true lumbar flexion measurement. *Spine, 17*(3), 345-348.

Milosavljevic, S., Milburn, P. D., & Knox, B. W. (2005). The influence of occupation on lumbar sagittal motion and posture. *Ergonomics, 48*(6), 657-667.

Mitchell, T., O'Sullivan, P. B., Smith, A., Burnett, A. F., Straker, L., Thornton, J., et al. (2009). Biopsychosocial factors are associated with low back pain in female nursing students: a cross-sectional study. *International Journal of Nursing Studies, 46*(5), 678-688.

Miyagi, M. M. D., Ishikawa, T. M. D., Kamoda, H. M. D., Suzuki, M. M. D., Murakami, K. M. D., Shibayama, M. M. D., et al. (2012). ISSLS Prize Winner: Disc Dynamic Compression in Rats Produces Long-Lasting Increases in Inflammatory Mediators in Discs and Induces Long-Lasting Nerve Injury and Regeneration of the Afferent Fibers Innervating Discs: A Pathomechanism for Chronic Discogenic Low Back Pain. *Spine, 37*(21), 1810-1818.

Mjøsund HL, Boyle E, Kjaer P, Mieritx RM, Skallgard T, & P., K. (2017). Clinically acceptable agreement between the ViMove wireless motion sensor system and the Vicon motion capture system when measuring lumbar region inclination motion in the sagittal and coronal planes. . *BMC Musculoskeletal Disorders, 18*(124).

Moher, D., Liberati, A., Tetzlaff, J., Altman, D., & (2009), T. P. G. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Ann Intern Med, 151*(4), 264-269.

Mokkink, L. B., Terwee, C. B., Patrick, D. L., Alonso, J., Stratford, P. W., Knol, D. L., et al. (2010). The COSMIN study reached international consensus on taxonomy, terminology, and definitions of measurement properties for health-related patient-reported outcomes. *Journal of Clinical Epidemiology, 63*(7), 737-745.

Mooney, V., Gulick, J., Perlman, M., Levy, D., Pozos, R., Leggett, S., et al. (1997). Relationships between myoelectric activity, strength, and MRI of lumbar extensor muscles in back pain patients and normal subjects. *Journal of Spinal Disorders, 10*(4), 348-356.

Morley, S., Linton, S., & Vlaeyen, J. (2015). *Single case research methodology in clinical pain management – an introduction and practical workshop.*

Morris, S. L., Lay, B., & Allison, G. T. Corset hypothesis rebutted — Transversus abdominis does not co-contract in unison prior to rapid arm movements. *Clinical Biomechanics*(0).

Moseley, G. L., & Hodges, P. W. (2006). Reduced variability of postural strategy prevents normalization of motor changes induced by back pain: A risk factor for chronic trouble? *Behavioral Neuroscience, 120*(2), 474-476.

Mosner, E. A., Bryan, J. M., Stull, M. A., & Shippee, R. (1989). A comparison of actual and apparent lumbar lordosis in black and white adult females. *Spine, 14*(3), 310-314.

Mulholland, R. (2008). The myth of lumbar instability: the importance of abnormal loading as a cause of low back pain. *European Spine Journal, 17*, 619-625.

Muller, B., Ilg, W., Giese, M. A., & Ludolph, N. (2017). Validation of enhanced kinect sensor based motion capturing for gait assessment. *PLoS ONE [Electronic Resource], 12*(4), e0175813.

Mulligan, B. R. (2004). *Manual therapy: "NAGS, SNAGS, MWMs"* (4th ed.). Wellington, New Zealand.

Nachemson, A. (1981). Disc Pressure Measurements. *Spine January/February, 6*(1), 93-97.

Nagin, D. (2005). *Group-based modeling development*. Cambridge: Harvard University Press.

Nattrass, C. L., Nitschke, J. E., Disler, P. B., Chou, M. J., & Ooi, K. T. (1999). Lumbar spine range of motion as a measure of physical and functional impairment: an investigation of validity. *Clinical Rehabilitation, 13*(3), 211-218.

Neblett, R., Mayer, T. G., Brede, E., & Gatchel, R. J. (2010). Correcting abnormal flexion-relaxation in chronic lumbar pain: responsiveness to a new biofeedback training protocol. *Clinical Journal of Pain, 26*(5), 403-409.

Neblett, R., Mayer, T. G., Brede, E., & Gatchel, R. J. (2014a). The effect of prior lumbar surgeries on the flexion relaxation phenomenon and its responsiveness to rehabilitative treatment. *The Spine Journal, 14*, 892-902.

Neblett, R., Mayer, T. G., Gatchel, R. J., Keeley, J., Proctor, T., Anagnostis, C., et al. (2003). Quantifying the lumbar flexion-relaxation phenomenon: theory, normative data, and clinical applications. *Spine, 28*(13), 1435-1446.

Nelson-Wong, E., Brendon, A., Csepe, D., Lancaster, D., & Callaghan, J. P. (2012). Altered muscle recruitment during extension from trunk flexion in low back pain developers. *Clinical Biomechanics, 27*, 994-998.

Nelson-Wong, E., & Callaghan, J. (2014). Transient Low Back Pain Development During Standing Predicts Future Clinical Low Back Pain in Previously Asymptomatic Individuals. *Spine, 39*(6), E379-E383.

Newcomer, K., Laskowski, E., Yu, B., Larson, D., & An, K. (2000). Repositioning error in low back pain: Comparing trunk repositioning error in subjects with chronic low back pain and control subjects. *Spine, 25*(2), 245-250.

Newcomer, K. L., Laskowski, E. R., Yu, B., Johnson, J. C., & An, K. N. (2000). Differences in repositioning error among patients with low back pain compared with control subjects. *Spine, 25*(19), 2488-2493.

Ng, J. K., Richardson, C. A., Kippers, V., Parnianpour, M., Ng, J. K. F., Richardson, C. A., et al. (2002). Comparison of lumbar range of movement and lumbar lordosis in back pain patients and matched controls. *Journal of Rehabilitation Medicine, 34*(3), 109-113.

NICE. (2016). *Low back pain and sciatica in over 16s: assessment and management: Assessment and non-invasive treatments*. National institute for clinical excellence (NICE) Guideline (NG59) Retrieved from https://www.nice.org.uk/guidance/ng59/evidence/full-guideline-assessment-and-noninvasive-treatments-pdf-2726158003.

Niggemann, P., Kuchta, J., Beyer, H., Grosskurth, D., Schulze, T., & Delank, K. (2011). Spondylolysis and Spondylolisthesis: Prevalence of Different Forms of Instability and Clinical Implications. *Spine, 36*(22), E1463-E1468.

Nitschke, J., Nattrass, C., Disler, P., Chou, M., & Ooi, K. (1999). Reliability of the American Medical Association Guides' Model for measuring spinal range of motion: its implication for whole-person impairment rating. *Spine, 24*(3), 262-268.

Norton, B., Sahrmann, S., & Van, D. L. (2004). Differences in Measurements of Lumbar Curvature Related to Gender and Low Back Pain. *Journal of Orthopaedic and Sports Physical Therapy, 34*(9), 524-534.

Nourbakhsh, M. R., Moussavi, S. J., & Salavati, M. (2001). Effects of lifestyle and work-related physical activity on the degree of lumbar lordosis and chronic low back pain in a Middle East population. *Journal of Spinal Disorders, 14*(4), 283-292.

Nouwen, A. (1983). EMG biofeedback used to reduce standing levels of paraspinal muscle tension in chronic low back pain. *Pain, 17*(4), 353-360.

Nylund, K., Asparouhoy, A., & Muthe'n, B. (2007). Deciding on the number of classes in latent class analysis and growth mixture modeling: a Monte Carlo simulation study. *Structural Equation Modelling, 14*, 535-569.

O'Connell, G. D., Vresilovic, E. J., & Elliott, D. M. (2011). Human intervertebral disc internal strain in compression: The effect of disc region, loading position, and degeneration. *Journal of Orthopaedic Research, 29*(4), 547-555.

O'Sullivan, K., O'Sullivan, P., O'Sullivan, L., & Dankaerts, W. (2012). What do physiotherapists consider to be the best sitting spinal posture? *Manual Therapy, 17*(5), 432-437.

O'Sullivan, K., Verschueren, S., Van Hoof, W., Ertanir, F., Martens, L., & Dankaerts, W. (2013). Lumbar repositioning error in sitting: Healthy controls versus people with sitting-related non-specific chronic low back pain (flexion pattern). *Manual Therapy, 18*(6), 526-532.

O'Sullivan, K. J., O'Sullivan, L., Campbell, A., O'Sullivan, P., & Dankaerts, W. (2012). Towards monitoring lumbo-pelvic posture in real-life situations: Concurrent validity of a novel posture monitor and a traditional laboratory-ased motion analysis system. *Manual Therapy, 17*, 77-83.

O'Sullivan, P., Caneiro, J., O'Keefe, M., Smith, A., Dankaerts, W., Fersum, K., et al. (2018). Cognitive functional therapy: An integrated behavioral approach for the targeted management of disabling low back pain. *Physical Therapy, 98*(5), 408-423.

O'Sullivan, P., Smith, A., Beales, D., & Straker, L. (2017). Understanding Adolescent Low Back Pain From a Multidimensional Perspective: Implications for Management. *Journal of Orthopaedic & Sports Physical Therapy, 47*(10), 741-751.

O'Sullivan, P., Twomey, L., & Allison, G. (1998). Altered abdominal muscle recruitment in patients with chronic back pain following a specific exercise intervention. *Journal of Orthopaedic and Sports Physical Therapy, 27*(2), 114-124.

O'Sullivan, P., Twomey, L. T., & Allison, G. T. (1997). Evaluation of specific stabilizing exercise in the treatment of chronic low back pain with radiologic diagnosis of spondylolysis or spondylolisthesis. *Spine, 22*(24), 2959-2967.

O'Sullivan, P. B. (2005a). 'Clinical instability' of the lumbar spine: its pathological basis, diagnosis and conservative management. In J. Boyling & G. Jull (Eds.), *Grieve's Modern Manual Therapy - The Vertebral Column* (3rd ed.). Edinburgh: Churchill Livingstone.

O'Sullivan, P. B. (2005). Diagnosis and classification of chronic low backpain disorders: Maladaptive movement and motor control impairments as underlying mechanism. *Manual Therapy, 10*, 242-255.

O'Sullivan, P. B., Burnett, A., Floyd, A. N., Gadsdon, K., Logiudice, J., Miller, D., et al. (2003). Lumbar repositioning deficit in a specific low back pain population. *Spine, 28*(10), 1074-1079.

O'Sullivan, P. B., Mitchell, T., Bulich, P., Waller, R., & Holte, J. (2006). The relationship beween posture and back muscle endurance in industrial workers with flexion-related low back pain. *Manual Therapy, 11*(4), 264-271.

Ogurkowska, M. B., & Lewandowski, J. (2013). Kinesiological analysis of movement of the human lumbar spine. *Gait and Posture, 38*, S105-S106.

Ohtori, S., Inoue, G., Miyagi, M., & Takahashi, K. (2015). Pathomechanisms of discogenic low back pain in humans and animal models. *The Spine Journal, 15*(6), 1347-1355.

Palsson, T., Hirata, R., & Graven-Nielsen, T. (2015). Experimental Pelvic Pain Impairs the Performance During the Active Straight Leg Raise Test and Causes Excessive Muscle Stabilization. *Clinical Journal of Pain, 31*(7), 642-651.

Paquet, N., Malouin, F., & Richards, C. (1994). Hip-spine movement interaction and muscle activation patterns during sagittal trunk movements in low back pain patients. *Spine, 15*(5), 596-603.

Parks, K. A., Crichton, K. S., Goldford, R. J., & McGill, S. M. (2003). A comparison of lumbar range of motion and functional ability scores in patients with low back pain: Assessment for range of motion validity. *Spine, 28*(4), 380-384.

Pengel, L. H., Refshauge, K. M., & Maher, C. G. (2004). Responsiveness of pain, disability, and physical impairment outcomes in patients with low back pain. *Spine, 29*(8), 879-883.

Petersen, T., Laslett, M., Thorsen, H., Manniche, C., Ekdahl, C., & Jacobsen, S. (2003). Diagnostic classification of non-specific low back pain. A new system integrating patho-anatomic and clinical categories. *Physiotherapy Theory & Practice, 19*(4), 213-237.

Petrofsky, J. S., Batt, J., Brown, J., Stacey, L., Bartelink, T., Le Moine, M., et al. (2008). Improving the outcomes after back injury by a core muscle strengthening program. *Journal of Applied Research, 8*(1), 62-75.

Pincus, T., Kent, P., Bronfort, G., Loisel, P., Pransky, G., & Hartvigsen, J. (2013). Twenty-five years with the biopsychosocial model of low back pain – is it time to celebrate? A report from the Odense Forum XII. *Spine, 38*(24), 2118-2123.

Poitras, S., Loisel, P., Prince, F., & Lemaire, J. (2000). Disability measurement in persons with back pain: a validity study of spinal range of motion and velocity. *Archives of Physical Medicine & Rehabilitation, 81*(10), 1394-1400.

Poosanthanasarn, N., Lohachit, C., Fungladda, W., Sriboorapa, S., Pulkate, C., Poosanthanasarn, N., et al. (2005a). An ergonomics intervention program to prevent worker injuries in a metal autoparts factory. *Southeast Asian Journal of Tropical Medicine & Public Health, 36*(2), 512-522.

Poosanthanasarn, N., Sriboorapa, S., Fungladda, W., Lohachit, C., Poosanthanasarn, N., Sriboorapa, S., et al. (2005b). Reduction of low back muscular discomfort through an applied ergonomics intervention program. *Southeast Asian Journal of Tropical Medicine & Public Health, 36 Suppl 4*, 262-270.

Pope, M., Bevins, T., Wilder, D., & Frymoyer, J. (1985). The relationship between anthropometric postural, muscular, and mobility characteristics of males aged 18-55. *Spine, 10*, 644-648.

Porter, J. L., & Wilkinson, A. (1997). Lumbar-hip flexion motion. A comparative study between asymptomatic and chronic low back pain in 18- to 36-year-old men. *Spine, 22*(13), 1508-1513; discussion 1513-1504.

Portney, L. G., & Watkins, M. P. (2009). *Foundations of clinical research: applications to practice* (3rd ed.). New Jersey: Pearson Prentice Hall.

Pranata, A., Perraton, L., El-Ansary, D., Clark, R., Fortin, K., Dettmen, T., et al. (2017). Lumbar extensor muscle force control is associated with disability in people with chronic low back pain. *Clinical Biomechanics, 46*, 46-51.

Pynt, J., Mackey, M. G., & Higgs, J. (2008). Kyphosed seated postures: Extending concepts of postural health beyond the office. *Journal of Occupational Rehabilitation, 18*(1), 35-45.

Rabey, M., Smith, A., Beales, D., Slater, H., & O'Sullivan, P. (2016). Differing Psychologically Derived Clusters in People With Chronic Low Back Pain are Associated With Different Multidimensional Profiles. *Clinical Journal of Pain, 32*(12), 1015-1027.

Rackwitz, B., DeBie, R., Ewert, T., & Stucki, G. (2006). Segmental stabilizing exercises and low back pain. What is the evidence? A systematic review of randomized controlled trials. *Clinical Rehabilitation, 20*, 553-567.

Rajasekaran, S., Bajaj, N., Tubaki, V., Kanna, R., & Shetty, A. (2013). ISSLS Prize Winner: The Anatomy of Failure in Lumbar Disc Herniation: An In Vivo, Multimodal, Prospective Study of 181 Subjects. *Spine, 38*(17), 1491-1500.

Ramond-Roquin, A., Bodin, J., Serazin, C., Parot-Schinkel, E., Ha, C., Richard, I., et al. (2015). Biomechanical constraints remain major risk factors for low back pain. Results from a prospective cohort study in French male employees. *The Spine Journal, 15*(4), 559-569.

Ratzon, N., & Froom, P. (2006). Postural control in nurses with and without low back pain. *Work, 26*(2), 141-145.

Review Manager (RevMan) (Version 5.0). (2008). Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration.

Review Manager (RevMan) Version 5.2 (Version 5.2). (2012) [computer program]. Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration.

Ribeiro, D. C., Sole, G., Abbott, J. H., & Milosavljevic, S. (2011). Cumulative postural exposure measured by a novel device: a preliminary study. *Ergonomics, 54*(9), 858-865.

Richardson, C. (1997). An alternative low back pain test?... O'Sullivan PB, Twomey L, Allison GT, Sinclair J, Miller K and Knox J: Altered patterns of abdominal muscle activation in patients with chronic low back pain. *Australian Journal of Physiotherapy 43*(3), 91.

Richardson, C., Jull, G., Hodges, P., & Hides, J. (1999). *Therapeutic exercise for spinal segmental stabilization in low back pain : scientific basis and clinical approach*. Edinburgh: Churchill Livingstone.

Rittweger, J., Just, K., Kautzsch, K., Reeg, P., & Felsenberg, D. (2002). Treatment of chronic lower back pain with lumbar extension and whole-body vibration exercise: A randomized controlled trial. *Spine, 27*(17), 1829-1834.

Ritvanen, T., Zaproudina, N., Nissen, M., Leinonen, V., & Hänninen, O. (2007). Dynamic Surface Electromyographic Responses in Chronic Low Back Pain Treated by Traditional Bone Setting and Conventional Physical Therapy. *Journal of Manipulative and Physiological Therapeutics, 30*(1), 31-37.

Roche-Leboucher, G., Petit-Lemanac'h, A., Bontoux, L., Dubus-Bausiere, V., Parot-Shinkel, E., Fanello, S., et al. (2011). Multidisciplinary Intensive Functional Restoration Versus Outpatient Active Physiotherapy in Chronic Low Back Pain: A Randomized Controlled Trial. *Spine, 36*(26), 2235-2242.

Roche, G., Ponthieux, A., Parot-Shinkel, E., Jousset, N., Bontoux, L., Dubus, V., et al. (2007). Comparison of a Functional Restoration Program With Active Individual Physical Therapy for Patients With Chronic Low Back Pain: A Randomized Controlled Trial. *Archives of Physical Medicine and Rehabilitation, 88*(10), 1229-1235.

Rodriguez-Soto, A., Jaworski, R., Jensen, A., Niederberger, B., Hargens, A., Frank, L., et al. (2013). Effect of Load Carriage on Lumbar Spine Kinematics. *Spine*.

Roland, M., & Fairbank, J. (2000). The Roland-Morris Disability Questionnaire and the Oswestry Disability Questionnaire. *Spine, 25*(24), 3115-3124.

Ronchi, A., Lech, M., Taylor, N., & Cosic, I. (2008). A reliability study of the new Back Strain Monitor based on clinical trials. *Conf Proc IEEE Eng Med Biol Soc. 693-6*, 693-696.

Rosenstiel, A. K., & Keefe, F. J. (1983). Coping Strategies Questionnaire (CSQ). *Keefe FJ, Ohio University, Athens, OH, 45701*(4).

Ross, R., & LaStayo, P. (1997). Clinical Assessment of Pain. In van Deusen J & B. D (Eds.), *Assessment in Occupational Therapy and Physical Therapy*. Philadelphia: WB Saunders Co.

Roussel, N., Nijs, J., Truijen, S., Vervecken, L., Mottram, S., Stassijns, G., et al. (2009). Altered breathing patterns during lumbopelvic motor control tests in chronic low back pain: a case-control study. *European Spine Journal, 18*(7), 1066-1073.

Ruhe, A., Fejer, R., & Walker, B. (2011). Center of pressure excursion as a measure of balance performance in patients with non-specific low back pain compared to healthy controls: a systematic review of the literature. *European Spine Journal, 20*(3), 358-368.

Russell, P., Pearcy, M. J., & Unsworth, A. (1993). Measurement of the range and coupled movements observed in the lumbar spine. *Rheumatology, 32*(6), 490-497.

Russo, C. (2009). The effects of exercise on bone. Basic concepts and implications for the prevention of fractures. *Clinical cases in mineral and bone metabolism, 6*(3), 223-228.

Sadler, S. G., Spink, M. J., Ho, A., De Jonge, X. J., & Chuter, V. H. (2017). Restriction in lateral bending range of motion, lumbar lordosis, and hamstring flexibility predicts the development of low back pain: a systematic review of prospective cohort studies. *BMC Musculoskeletal Disorders, 18*(1), 179.

Sahrmann S. (2002). Movement impairment syndromes of the lumbar spine.In: Diagnosis and treatment of movement impairment syndromes. *Diagnosis and treatment of movement impairment syndromes.* (1st ed., pp. 5-118). St. Loius: Mosby Inc.

Sahrmann, S. A. (2011). *Movement system impairment syndromes of the extremities, cervical and thoracic spines* (S. A. Sahrmann Ed.). St. Louis, Missouri: Elsevier,Mosby Inc.

Saragiotto, B., Maher, C., Yamato, T., Cost, L., Menezes, L., Ostelo, R., et al. (2016). Motor control exercise for nonspecific low back pain. *Spine, 41*(16), 1284-1295.

Scannell, J., & McGill, S. (2003). Lumbar posture-should it, and can it, be modified? A study of passive tissue stiffness and lumbar position during activities of daily living. *Physical Therapy, 83*(10), 907-917.

Schilder, A., Hoheisel, U., Magerl, W., Benrath, J., Klein, T., & Treede, R. (2014). Sensory findings after stimulation of the thoracolumbar fascia with hypertonic saline suggest its contribution to low back pain. *Pain, 155*(2), 222-231.

Schmelzer, A., Salt, E., Wiggins, A., Crofford, L., Bush, H., & Mannino, D. (2016). Role of Stress and Smoking as Modifiable Risk Factors for Nonpersistent and Persistent Back Pain in Women. *Clinical Journal of Pain, 32*(3), 232-237.

Schmidt, H., Galbusera, F., Rohlmann, A., & Shirazi-Adl, A. (2013). What have we learned from finite element model studies of lumbar intervertebral discs in the past four decades? *Journal of Biomechanics, 46*(14), 2342-2355.

Schmidt, H., Heuer, F., Drumm, J., Klezl, Z., Claes, L., Wilke, H. J., et al. (2007). Application of a calibration method provides more realistic results for a finite element model of a lumbar spinal segment. *Clinical Biomechanics, 22*(4), 377-384.

Schmidt, H., Kettler, A., Heuer, F., Simon, U., Claes, P., & Wilke, H. (2007). Intradiscal Pressure, Shear Strain, and Fiber Strain in the Intervertebral Disc Under Combined Loading. *Spine, 32*(7), 748-755.

Schober, P. (1937). The lumbar vertebral column and back ache. *Munchener Medizinische Wochenschrift, 84*, 336.

Schofield, D. J., Callander, E. J., Shrestha, R. N., Percival, R., Kelly, S. J., & Passey, M. E. (2012). Labor force participation and the influence of having back problems on income poverty in Australia. *Spine* 37(13) 1156-1163.

Seay, J. F., E.A, & Hamill, J. (2011). Low back pain status affects pelvis-trunk coordination and variability during walking and running. *Clinical Biomechanics, 26*(6), 572-578.

Serbic, D. M., & Pincus, T. P. (2014). Pain-related Guilt in Low Back Pain. *Clinical Journal of Pain, 30*(12), 1062-1069.

Shahvarpour, A., Henry, S. M., Preuss, R., Mecheri, H., & Larivière, C. (2017). The effect of an 8-week stabilization exercise program on the lumbopelvic rhythm and flexion-relaxation phenomenon. *Clinical Biomechanics, 48*, 1-8.

Sheeran, L., Sparkes, V., Caterson, B., Busse-Morris, M., & van Deursen, R. (2012). Spinal position sense and trunk muscle activity during sitting and standing in nonspecific chronic low back pain: classification analysis. *Spine, 37*(8), E486-495.

Sherrington, C., & Lord, S. (1997). Home exercise to improve strength and walking velocity after hip fracture: A randomized controlled trial. *Archives of Physical Medicine & Rehabilitation, 78*(2), 208-212.

Shiozawa, S., Hirata, R. P., & Graven-Nielsen, T. (2015). Center of Pressure Displacement of Standing Posture during Rapid Movements Is Reorganised Due to Experimental Lower Extremity Muscle Pain. *PLoS ONE [Electronic Resource], 10*(12), e0144933.

Shirazi-Adl, A., & Parnianpour, M. (1996). Role of Posture in Mechanics of the Lumbar Spine in Compression. *Journal of Spinal Disorders, 9*(4), 277-286.

Shum, G., Crosbie, J., & Lee, R. (2005). Symptomatic and asymptomatic movement coordination of the lumbar spine and hip during an everyday activity. *Spine, 30*(23), E697-702.

Shum, G. L., Crosbie, J., & Lee, R. Y. W. (2007). Three-Dimensional Kinetics of the Lumbar Spine and Hips in Low Back Pain Patients During Sit-to-Stand and Stand-to-Sit. *Spine, 32*(7), E211-E219.

Silfies, S. P., Bhattacharya, A., Biely, S., Smith, S. S., Giszter, S., Silfies, S. P., et al. (2009a). Trunk control during standing reach: A dynamical system analysis of movement strategies in patients with mechanical low back pain. *Gait & Posture, 29*(3), 370-376.

Silfies, S. P., Mehta, R., Smith, S. S., & Karduna, A. R. (2009b). Differences in Feedforward Trunk Muscle Activity in Subgroups of Patients With Mechanical Low Back Pain. *Archives of Physical Medicine and Rehabilitation, 90*(7), 1159-1169.

Slade, S. C., & Keating, J. L. (2006). Trunk-strengthening exercises for chronic low back pain: a systematic review. *Journal of Manipulative & Physiological Therapeutics, 29*(2), 163-173.

Slade, S. C., & Keating, J. L. (2007). Unloaded movement facilitation exercise compared to no exercise or alternative therapy on outcomes for people with nonspecific chronic low back pain: a systematic review. *Journal of Manipulative & Physiological Therapeutics, 30*(4), 301-311.

Smith, A., O'Sullivan, P., & Straker, L. (2008). Classification of sagittal thoraco-lumbo-pelvic alignment of the adolescent spine in standing and its relationship to low back pain. *Spine, 33*(19), 2101-2107.

Smith, B. E., Littlewood, C., & May, S. (2014). An update of stabilisation exercises for low back pain: a systematic review with meta-analysis. *BMC Musculoskeletal Disorders, 15*(1), 416.

Smith, J., & Kulig, K. (2016). Altered Multifidus Recruitment During Walking in Young Asymptomatic Individuals With a History of Low Back Pain. *Journal of Orthopaedic & Sports Physical Therapy, 46*(5), 365-374.

Smith, M., Coppieters, M. W., & Hodges, P. W. (2005). Effect of experimentally induced low back pain on postural sway with breathing. *Experimental Brain Research, 166*(1), 109-117.

Soukup, M. G., Glomsrod, B., Lonn, J. H., Bo, K., & Larsen, S. (1999). The effect of a Mensendieck exercise program as secondary prophylaxis for recurrent low back pain. A randomized, controlled trial with 12-month follow-up. *Spine, 24*(15), 1585-1591; discussion 1592.

Spitzer, W. O., Arsenault, S., Abenhaim, L., Dupuis, M., Belanger, A., Bloch, R., et al. (1987). Quebec Task Force on spinal disorders - Scientific approach to the assessment and management of activity-related spinal disorders - a monograph for clinicians. *Spine, 12*(7), 1-59.

Stanton, T. R., Latimer, J., Maher, C. G., Hancock, M., Stanton, T. R., Latimer, J., et al. (2009). Definitions of recurrence of an episode of low back pain: a systematic review. *Spine, 34*(9), E316-322.

StataCorp. (2011). Stata Statistical Software: Release 12. College Station, TX: StataCorp LP.

Steele, J., Bruce-Low, S., & Smith, D. (2014). A reappraisal of the deconditioning hypothesis in low back pain: review of evidence from a triumvirate of research methods on specific lumbar extensor deconditioning. *Current Medical Research and Opinion, 30*(5), 865-911.

Steiger, F., Wirth, B., De Bruin, E. D., & Mannion, A. (2011). Is a positive clinical outcome after exercise therapy for chronic non-specific low back pain contingent upon a corresponding improvement in the targeted aspect(s) of performance? A systematic review. *European Spine Journal*.

Stevens, M., Steffens, D., Ferreira, M., Latimer, J., Li, Q., Blyth, F., et al. (2016). Patients' and Physiotherapists' Views on Triggers for Low Back Pain. *Spine, 41*(4), E218-E224.

Stuge, B., Veierod, M. B., Laerum, E., & Vollestad, N. (2004). The efficacy of a treatment program focusing on specific stabilizing exercises for pelvic girdle pain after pregnancy: a randomized controlled trial. *Spine, 29*(4), 351-359.

Sullivan, M. S., Shoaf, L. D., & Riddle, D. L. (2000). The relationship of lumbar flexion to disability in patients with low back pain. *Physical Therapy, 80*(3), 240-250.

Sung, P. S., Park, W.-H., & Kim, Y. H. (2012). Three-dimensional kinematic lumbar spine motion analyses of trunk motion during axial rotation activities. *Journal of Spinal Disorders & Techniques, 25*(3), E74-80.

Sung, P. S., & Sung, P. S. (2003). Multifidi muscles median frequency before and after spinal stabilization exercises. *Archives of Physical Medicine & Rehabilitation, 84*(9), 1313-1318.

Suni, J., Rinne, M., Natri, A., Statistisian, M. P., Parkkari, J., & Alaranta, H. (2006). Control of the lumbar neutral zone decreases low back pain and improves self-evaluated work ability: a 12-month randomized controlled study. *Spine, 31*(18), E611-620.

Suri, P., Rainville, J., de Schepper, E., Martha, J., Hartigan, C., & Hunter, D. (2018). Do Physical Activities Trigger Flare-ups During an Acute Low Back Pain Episode?: A Longitudinal Case-Crossover Feasibility Study. *Spine, 43*(6), 427-433.

Tafazzol, A., Arjmand, N., Shirazi-Adl, A., & Parnianpour, M. (2014). Lumbopelvic rhythm during forward and backward sagittal trunk rotations: Combined in vivo measurement with inertial tracking device and biomechanical modeling. *Clinical Biomechanics, 29*, 7+.

Taimela, S., & Harkapaa, K. (1996). Strength, Mobility, Their Changes, and Pain Reduction in Active Functional Restoration for Chronic Low Back Disorders. *Journal of Spinal Disorders, 9*(4), 306-312.

Taimela, S., Kankaanpaa, M., & Luoto, S. (1999). The effect of lumbar fatigue on the ability to sense a change in lumbar position. A controlled study. *Spine, 24*(13), 1322-1327.

Takala, E., & Viikari, J. E. (2000). Do functional tests predict low back pain? *Spine, 25*(16), 2126-2132.

Taylor, J. B., Goode, A. P., George, S. Z., & Cook, C. E. (2014). Incidence and risk factors for first-time incident low back pain: a systematic review and meta-analysis. *Spine Journal: Official Journal of the North American Spine Society, 14*(10), 2299-2319.

Teyhen, D. S., Flynn, T. W., Childs, J. D., & Abraham, L. D. (2007). Arthrokinematics in a subgroup of patients likely to benefit from a lumbar stabilization exercise program. *Physical Therapy, 87*(3), 313-325.

Thomas, J. S., & France, C. R. (2007). Pain-related fear is associated with avoidance of spinal motion during recovery from low back pain. *Spine, 32*(16), E460–E466.

Thomas, J. S., France, C. R., Lavender, S. A., & Johnson, M. R. (2008). Effects of fear of movement on spine velocity and acceleration after recovery from low back pain. *Spine, 33*, 564–570.

Tong, M. H., Mousavi, S. J., Kiers, H., Ferreira, P., Refshauge, K., & van Dieen, J. (2017). Is There a Relationship Between Lumbar Proprioception and Low Back Pain? A Systematic Review With Meta-Analysis. *Archives of Physical Medicine & Rehabilitation, 98*(1), 120-136.e122.

Treede, R., Rief, W., Barke, A., Aziz, Q., Bennett, M., Benoliel, R., et al. (2015). A classification of chronic pain for ICD-11. *Pain, 156*(6), 1003-1007.

Troke, M., Moore, A. P., Maillardet, F. J., & Cheek, E. (2005). A normative database of lumbar spine ranges of motion. *Manual Therapy, 10*(3), 198-206.

Troke, M., Moore, A. P., Maillardet, F. J., Hough, A., & Cheek, E. (2001). A new, comprehensive normative database of lumbar spine ranges of motion. *Clinical Rehabilitation, 15*(4), 371-379.

Troup, J. D. (1987). The perception of back pain and the role of psychophysical tests of lifting capacity. *Spine, 12*(7), 645-657.

Troyanovich, S. J., Harrison, D. E., & Harrison, D. D. (1998). Structural rehabilitation of the spine and posture: rationale for treatment beyond the resolution of symptoms.*Journal of Manipulative and Physiological Therapeutics, 21*(1), 37-50.

Trudelle-Jackson, E., Fleisher, L. A., Borman, N., Morrow, J. R., Jr., & Frierson, G. M. (2010). Lumbar spine flexion and extension extremes of motion in women of different age and racial groups: the WIN Study. *Spine, 35*(16), 1539-1544.

Trudelle-Jackson, E., Sarvaiya-Shah, S. A., & Wang, S. S. (2008). Interrater reliability of a movement impairment-based classification system for lumbar spine syndromes in patients with chronic low back pain. *Journal of Orthopaedic and Sports Physical Therapy, 38*(6), 371-376.

Tsai, Y., Sell, T., Smoliga, J., Myers, J., Learman, K., & Lephart, S. (2010). A comparison of physical characteristics and swing mechanics between golfers with and without a history of low back pain. *Journal of Orthopaedic and Sports Physical Therapy, 40*(7), 430-438.

Tsang, S., Szeto, G., Li, L., Wong, D., Yip, M., & Lee, R. (2017). The effects of bending speed on the lumbo-pelvic kinematics and movement pattern during forward bending in people with and without low back pain. *BMC Musculoskeletal Disorders, 18*, 157-168.

Tsao, H., Druitt, T. R., Schollum, T. M., & Hodges, P. W. (2010). Motor Training of the Lumbar Paraspinal Muscles Induces Immediate Changes in Motor Coordination in Patients With Recurrent Low Back Pain. *The Journal of Pain, 11*(11), 1120-1128.

Turner, J. A., Franklin, G., Heagerty, P. J., Wu, R., Egan, K., Fulton-Kehoe, D., et al. (2004). The association between pain and disability. *Pain, 112*(3), 307-314.

Unsgaard-Tondel, M., Fladmark, A. M., Salveson, O., & Vasseljen, O. (2010). Motor control exercises, sling exercises and general exercises for patients with CLBP: a RCT with 1 year follow-up. *Physical Therapy, 90*(10), 1-14.

National_Library_of_Medicine (USA). (2012). http://www.ncbi.nlm.nih.gov/mesh.

Vaisy, M. P., Gizzi, L. P., Petzke, F. M. D., Consmuller, T. P., Pfingsten, M. P., & Falla, D. P. (2015). Measurement of Lumbar Spine Functional Movement in Low Back Pain. *Clinical Journal of Pain, 31*(10), 876-885.

Van Daele, U., Hagman, F., Truijen, S., Vorlat, P., Van Gheluwe, B., PhD, et al. (2010). Decrease in postural sway and trunk stiffness during cognitive dual-task in nonspecific chronic low back pain patients, performance compared to healthy control subjects. *Spine, 35*(5), 583-589.

van den Hoorn, W., Hug, F., Hodges, P. W., Bruijn, S. M., & van Dieen, J. H. (2015). Effects of noxious stimulation to the back or calf muscles on gait stability. *Journal of Biomechanics, 48*(15), 4109-4115.

Van Dillen, L. R., Sahrmann, S. A., Norton, B. J., Caldwell, C. A., McDonnell, M. K., Bloom, N., et al. (2003). The effect of modifying patient-preferred spinal movement and alignment during symptom testing in patients with low back pain: a preliminary report. *Archives of Physical Medicine & Rehabilitation, 84*(3), 313-322.

van Heeswijk, V., Thambyah, A., Robertson, P., & Broom, N. (2017). Posterolateral Disc Prolapse in Flexion Initiated by Lateral Inner Annular Failure: An Investigation of the Herniation Pathway. *Spine, 42*(21), 1604-1613.

Van Hoof, W., Volkaerts, K., O'Sullivan, K., Verschueren, S., & Dankaerts, W. (2012). Comparing lower lumbar kinematics in cyclists with low back pain (flexion pattern) versus asymptomatic controls – field study using a wireless posture monitoring system. *Manual Therapy, 17*(4), 312-317.

van Middelkoop, M., Rubinstein, S. M., Verhagen, A. P., Ostelo, R. W., Koes, B. W., & van Tulder, M. W. (2010). Exercise therapy for chronic nonspecific low-back pain. *Best Practice & Research in Clinical Rheumatology, 24*(2), 193-204.

Vasseljen, O., & Fladmark, A. M. (2010). Abdominal muscle contraction thickness and function after specific and general exercises: A randomized controlled trial in chronic low back pain patients. *Manual Therapy, 15*(5), 482-489.

Vasseljen, O., Unsgaard-Tondel, M., Westad, C., & Mork, P. (2012). Effect of Core Stability Exercises on Feedforward Activation of Deep Abdominal Muscles in Chronic Low Back Pain: A Randomized Controlled Trial. *Spine.*

Verhagen, A. P., de Vet, H. C. W., de Bie, R. A., Kessels, A. G. H., Boers, M., Bouter, L. M., et al. (1998). The Delphi List: A Criteria List for Quality Assessment of Randomized Clinical Trials for Conducting Systematic Reviews Developed by Delphi Consensus. *Journal of Clinical Epidemiology, 51*(12), 1235-1241.

Vibe Fersum, K., O'Sullivan, P. B., Kvale, A., & Skouen, J. S. (2008). Inter-examiner reliability of a classification system for patients with non-specific low back pain. *Manual Therapy.*

Villumsen, M., Madeleine, P., Jorgensen, M., Holtermann, A., & Samani, A. (2016). The variability of the trunk forward bending in standing activities during work vs. leisure time. *Applied Ergonomics, 58*, 273-280.

Vos, T., Abajobir, A. A., Abate, K. H., Abbafati, C., Abbas, K. M., Abd-Allah, F., et al. (2017). Global, regional, and national incidence, prevalence, and years lived with disability for 328 diseases and injuries for 195 countries, 1990-2016: a systematic analysis for the Global Burden of Disease Study 2016. *The Lancet, 390*(10100), 1211-1259.

Vos, T., Flaxman, A. D., Naghavi, M., Lozano, R., Michaud, C., Ezzati, M., et al. (2012). Years lived with disability (YLDs) for 1160 sequelae of 289 diseases and injuries 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *The Lancet, 380*(9859), 2163-2196.

Vos, T., & GBD2015Collaborators. (2016a). Global, regional, and national disability-adjusted life-years (DALYs) for 315 diseases and injuries and healthy life expectancy (HALE), 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *The Lancet, 388*(10053), 1603-1658.

Vos, T., & GBD2016Collaborators. (2016b). Global, regional, and national incidence, prevalence, and years lived with disability for 310 diseases and injuries, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *The Lancet, 388*(10053), 1545-1602.

Waddell, G. (1987). A new clinical model for the treatment of low-back pain. *Spine, 12*(7), 632-644.

Waddell, G. (1996). Low Back Pain: A Twentieth Century Health Care Enigma. *Spine, 21*(24), 2820-2825.

Waddell, G., Somerville, D., Henderson, I., & Newton, M. (1992). Objective clinical evaluation of physical impairment in chronic low back pain. *Spine, 17*(6), 617-628.

Wade, K., Robertson, P., Thambyah, A., & Broom, N. (2014). How Healthy Discs Herniate: A Biomechanical and Microstructural Study Investigating the Combined Effects of Compression Rate and Flexion. *Spine, 39*(13), 1018-1028.

Wallwork, T. L., Stanton, W. R., Freke, M., & Hides, J. A. (2009). The effect of chronic low back pain on size and contraction of the lumbar multifidus muscle. *Manual Therapy, 14*(5), 496-500.

Wand, B. M., O'Connell, N. E., Di Pietro, F., & Bulsara, M. (2011). Managing chronic nonspecific low back pain with a sensorimotor retraining approach: exploratory multiple-baseline study of 3 participants. *Physical Therapy, 91*(4), 535-546.

Watson, P., Booker, C., Main, C., & Chen, A. (1997). Surface electromyography in the identification of chronic low back pain patients: the development of the flexion relaxation ratio. *Clinical Biomechanics, 12*, 165-171.

Watters, W., Baisden, J., Gilbert, T., Kreiner, S., Resnick, D., Bono, C., et al. (2008). Degenerative lumbar spinal stenosis: an evidence-based clinical guideline for the diagnosis and treatment of degenerative lumbar spinal stenosis. *The Spine Journal, 8*(2), 305-310.

Weiner, B. K. (2008). The biopsychosocial model and spine care. *Spine, 33*(2), 219–223.

Weinstein, J., Tosteson, T., Lurie, J., Tosteson, A., Blood, E., Hanscom, B., et al. (2008). Surgical versus Nonsurgical Therapy for Lumbar Spinal Stenosis. *The New England Journal of Medicine, 358*(8), 794-810.

Westaway, M., Stratford, P., & Binkley, J. (1988). The patient-specific functional scale: validation of its use in persons with neck dysfunction. *Journal of Orthopaedic and Sports Physical Therapy 27*, 331-338.

Whiting, P. F., Weswood, M. E., Rutjes, A. W., Reitsma, J. B., Bossuyt, P. N., & Kleijnen, J. (2006). Evaluation of QUADAS, a tool for the quality assessment of diagnostic accuracy studies. *BMC Medical Research Methodology2006,, 6*(9), doi:10.1186/1471-2288-1186-1189.

Widerstrom, B., Olofsson, N., Arvidsson, I., Harms-Ringdahl, K., & Larsson, U. E. (2012). Inter-examiner reliability of a proposed decision-making treatment based classification system for low back pain patients. *Manual Therapy, 17*(2), 164-171.

Wilke, H. J., Neef, P., Caimi, M., & Hoogland, P. H. (1999). New In Vivo Measurements of Pressures in the Intervertebral Disc in Daily Life. *Spine, 24*(8), 755-762.

Williams, M. M., Hawley, J. A., McKenzie, R. A., & van Wijmen, P. M. (1991). A comparison of the effects of two sitting postures on back and referred pain. *Spine, 16*(10), 1185-1191.

Willigenburg, N. W., Kingma, I., Hoozemans, M. J. M., & van Dieen, J. H. (2013). Precision control of trunk movement in low back pain patients. *Human Movement Science, 32*(1), 228-239.

Willigenburg, N. W., Kingma, I., & van Dieen, J. H. (2012). Precision control of an upright trunk posture in low back pain patients. *Clinical Biomechanics, 27*(9), 866-871.

Wong, A., Parent, E., Funabashi, M., & Kawchuk, G. (2014). Do changes in transversus abdominis and lumbar multifidus during conservative treatment explain changes in clinical outcomes related to nonspecific low back pain? A systematic review. *The Journal of Pain, 15*(4), 377.e371-377.e335.

Wong, A., Parent, E., Funabashi, M., Stanton, T., & Kawchuk, G. (2013). Do various baseline characteristics of transversus abdominis and lumbar multifidus predict clinical outcomes in nonspecific low back pain? A systematic review. *Pain, 154*(12), 2589-2602.

Wong, A., Parent, E., Prasad, N., Huang, C., Chan, M., & Kawchuk, G. (2016). Does experimental low back pain change posteroanterior lumbar spinal stiffness and trunk muscle activity? A randomized crossover study. *Clinical Biomechanics, 34 Supplement*(C), 45-52.

Wong, T. K., Lee, R. Y., Wong, T. K. T., & Lee, R. Y. W. (2004). Effects of low back pain on the relationship between the movements of the lumbar spine and hip. *Human Movement Science, 23*(1), 21-34.

Wong, W. Y., & Wong, M. S. (2008). Trunk postural monitoring with inertial sensors. *European Spine Journal, 17*(5), 743-753.

Woodman, J. P., & Moore, N. R. (2012). Evidence for the effectiveness of Alexander Technique lessons in medical and health-related conditions: a systematic review. *International Journal of Clinical Practice, 66*(1), 98-112.

Yang, H., Haldeman, S., Lu, M. L., & Baker, D. (2016). Low Back Pain Prevalence and Related Workplace Psychosocial Risk Factors: A Study Using Data From the 2010 National Health Interview Survey. *Journal of Manipulative & Physiological Therapeutics, 39*(7), 459-472.

Youdas, J. W., Garrett, T. R., Egan, K. S., & Therneau, T. M. (2000). Lumbar lordosis and pelvic inclination in adults with chronic low back pain. *Physical Therapy, 80*(3), 261-275.

Youdas, J. W., Garrett, T. R., Harmsen, S., Suman, V. J., & Carey, J. R. (1996). Lumbar lordosis and pelvic inclination of asymptomatic adults. *Physical Therapy, 76*(10), 1066-1081.

Zale, E., Lange, K., Fields, S., & Ditre, J. (2013). The relation between pain-related fear and disability: A metaanalysis. *Journal of Pain, 14*(10), 1019-1030.

Zuberbier, O., Kozlowski, A., Hunt, D., Berkowitz, J., Schultz, I., Crook, J., et al. (2001). Analysis of the convergent and discriminant validity of published lumbar flexion, extension, and lateral flexion scores. *Spine, 26*(20), E472-478.