The impact of footwear on the gait of younger children

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Monash University in 2021
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Thesis Abstract

Footwear plays a number of different roles for younger children. While there has been research aiming to understand the impact of footwear on the gait of older children, there is little known about the impact of footwear on walking and running in younger children, in particular those with an immature gait. Given the scale of the footwear industry and its impact, it is important to study these factors in younger children. In clinical practice, parents often seek advice about the best type of footwear for their young child and there is very limited information to guide these recommendations.

Research aims:

This research determined the impact of footwear on younger children's walking and running. The literature was reviewed and determines what impact shoe features have on younger children's gait, including the differences between shoe sole flexibility compared to bare feet. In particular, this research addressed the differences in spatiotemporal measures of younger children's gait comparing soft soled footwear compared to bare feet, a comparison of soft versus hard soled footwear and an overview of the challenges of completing surface electromyography in this younger age group.

Research overview:

This thesis reports the findings from research projects that were undertaken to address the research aims, including the methodology and clinical implications of the research findings. A systematic review of the literature found shoes affect younger children's gait in spatiotemporal gait aspects, similar to those seen in older children. There is limited evidence on effects of particular shoe features such as sole hardness, on gait, and no evidence of any changes in muscle activation patterns. Our gait study also found that shoes affect the gait of young children by increasing velocity, cadence, step time and step length compared to bare feet, similar to that of older children. Our study also proposed that clinicians can cautiously inform parents of the minimal impact of the soft-soled footwear used in this study on walking

and running, however it is not the same as a child walking in bare feet. The EMG data were unable to be adequately analysed to determine if there were any differences observed in muscle activity in the different footwear types and Shore hardness. While this provided insufficient data that could be interpreted and analysed, our work did produce feasibility findings, adding to the overall structure of this thesis.

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 two original papers published in peer reviewed journals and one submitted publication currently under review. The core theme of the thesis is the impact of footwear on gait in younger children. The ideas, development and writing up of all the papers in the thesis were the principal responsibility of myself, the student, working within the Department of Physiotherapy, Faculty of Medicine, Nursing and Health Sciences under the supervision of A/Prof Cylie Williams, Dr Kelly-Ann Bowles and Dr Luke Perraton. The inclusion of co-authors reflects the fact that the work came from active collaboration between researchers and acknowledges input into team-based research**.**

In the case of Chapters 2, 4 and 5, my contribution to the work involved the following:

Thesis Chapter	**Publication Title**	**Status** *(published, in press, accepted or returned for revision)*	**Nature and % of student contribution**	**Co-author name(s) Nature and % of Co-author's contribution***	**Co-author(s), Monash student Y/N***
2	*The impact of shoe flexibility on gait, pressure and muscle activity of young children*	*Published*	*70%. Concept and data collection, review of the literature, results interpretation and writing first draft*	*A/Prof Cylie Williams, concept, review of literature, results interpretation, input into manuscript: 10%* *Dr. Kelly-Ann Bowles, study design, data collection, input into manuscript 10%* *Dr. Luke Perraton Data analysis, input into manuscript 10%*	*No*
4	*A comparison of young children's spatiotemporal measures of walking and*	*Published*	70%. Study design, data collection, results interpretation and writing of first draft	*A/Prof Cylie Williams, study design, data collection, results interpretation, revision of manuscript 10%*	*No*

	running in three common types of footwear compared to bare feet			*Dr. Kelly-Ann Bowles, study design, data collection, input into manuscript 10%* *Dr. Luke Perraton Study design, data collection, results interpretation, input into manuscript 10%*	
5	*Comparison of young children's spatiotemporal measures of walking and running soft versus hard soled*	*Under review*	70%. Study design, data collection, results interpretation and writing of first draft	*A/Prof Cylie Williams, study design, data collection, results interpretation, revision of manuscript 10%* *Dr. Kelly-Ann Bowles, study design, data collection, input into manuscript 10%* *Dr. Luke Perraton Study design, data collection, results interpretation, input into manuscript 10%*	*No*

Chapter 2

SC, CW, LP & KAB conceived and contributed to the study design. SC, LP & CW contributed to the critical review of the literature. SC, CW, LP & KAB interpreted the results. SC drafted the manuscript, SC, CW, LP & KAB revised the manuscript for important intellectual content. All authors approved current version of the manuscript that has been published.

Chapter 4

SC, CW, LP & KAB conceived and contributed to the study design. SC, CW, LP & KAB were responsible for data collection. SC, LP, CW interpreted the results. SC drafted the manuscript. SC, CW, LP & KAB revised the manuscript for important intellectual content. All authors approved current version of the manuscript that has been published.

Chapter 5

SC, CW, LP &KAB conceived and contributed to the study design. SC drafted the manuscript with revision and support from CW, LP & KAB. The final manuscript was revised by CW, LP, & KAB for intellectual content. All authors approved the current version of the manuscript that has been submitted for publication.

I have renumbered sections of submitted or published papers in order to generate a consistent presentation within the thesis.

Student signature: **Date:** 1/12/2020

The undersigned hereby certify 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 the respective contributions of the authors.

Main Supervisor signature: **Date:** 10/02/2020

Supervisor signature: **Date:** 17/12/2020

Supervisor signature: **Date:** 10/02/2020

Research output associated with this thesis

Publications during enrolment

Cranage, S., Perraton, L., Bowles, KA. Williams C.M. The impact of shoe flexibility on gait, pressure and muscle activity of young children. A systematic review. *J Foot Ankle Res* **12,** 55 (2019). https://doi.org/10.1186/s13047-019-0365-7

Cranage, S., Perraton L., Bowles KA., Williams C. (2020). A comparison of young children's spatiotemporal measures of walking and running in three common types of footwear compared to bare feet. Gait Posture; **81**, 218-24. https://doi.org/10.1016/j.gaitpost.2020.07.147

Publications under review

Cranage, S., Perraton L., Bowles KA., Williams C. (under review). A comparison of young children's spatiotemporal gait measures in three common types of footwear with different sole hardness (Gait & Posture).

Peer reviewed presentations during candidature

'Footwear and the impact on Toddler's Gait', Footwear Biomechanics Symposium, 2019, Kananaskis, Canada.

'Footwear and the impact on Toddler's Gait', Podiatry National Conference: 2019, Adelaide, Australia

'Footwear and the impact on Toddler's Gait', Peninsula Health Research Week, 2019

'Footwear and the impact on Toddler's Gait', Podiatry Victorian State Conference: 2018, Melbourne, Australia (Invited speaker)

Industry report

Bobux International Pty Ltd industry report

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Bobux Pty. Ltd. in kind contribution supplied 180 pairs of shoes for the study with an estimated retail value of $12,600.

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I wish to acknowledge and express my gratitude to the following organisations and professions who have assisted me throughout my study

Organisation Acknowledgments

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Bobux Pty Ltd who provided all of the footwear for the children in the study.

I hope this piece of work will assist clinicians, families, footwear manufacturers and companies to understand more about young children's footwear.

Professional and personal acknowledgements

Thank you to my amazing team of supervisors; Associate Professor Cylie Williams, Dr Luke Perraton and Dr Kelly-Ann Bowles for all of your support throughout the journey. Your passion for research, expertise in your respective fields, patience and support throughout this time has assisted me greatly in developing a new skillset in the area of research.

Cylie, thank you for your belief in my ability to complete this study. You always continued to encourage me throughout the process despite it taking me a long time. Thank you for your guidance, continually challenging me and allowing me to ask dumb questions. Your attention to detail and the strong support that you have shown me has not gone unnoticed. Even when you have been really busy, you have always found the time to help me or explain things simply. Your feedback along the way has always been timely, easy to follow and invaluable (even if red is the colour of love). Thank you for supporting me to present at my first international conference in Canada. It is an experience I will never forget and thank you for calming my nerves. You have always pushed me outside of my comfort zone to help me grow as a researcher, clinician and a person, and I will be forever thankful for that. You rock!

Kelly, thank you for your expertise and your calm nature. Your feedback always gave me a new perspective which assisted in expanding my research knowledge. Your biomechanics and EMG knowledge brought a new outlook to the research that was so valuable. Your passion for research and supporting post graduate students is always evident and I felt very lucky to have you there for support.

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To all of the children and families who participated in the research. Thank you for giving up your time to come along for the testing. We all had a lot of fun and thank you to the kids for providing a lot of fun and laughs during testing. This wouldn't have been possible without you all. Thank you to Grace Bowles who gave up time in her holidays to help us with the huge job of testing all the kids within one week.

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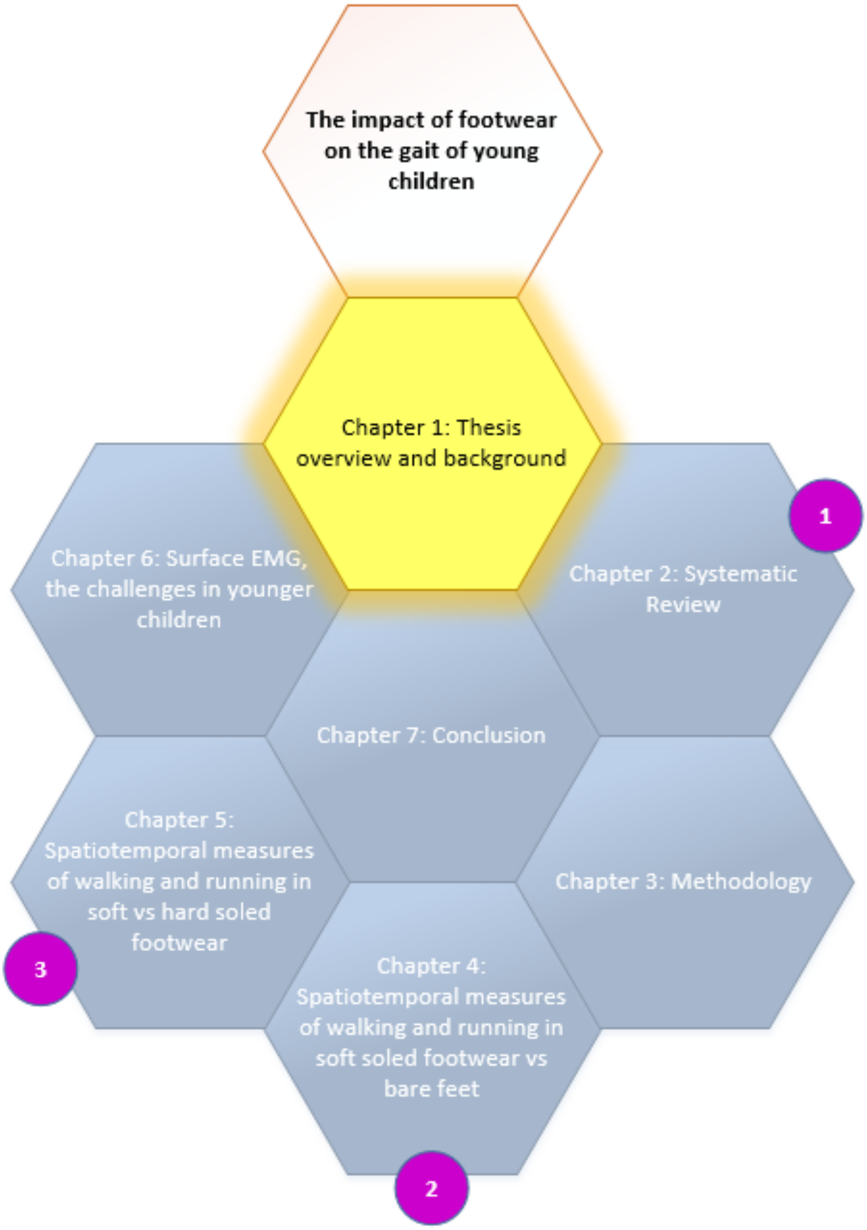
Chapter 1: Thesis overview and background

1.1 Preamble



This chapter summarises the gait cycle and understanding of the spatiotemporal measures of gait. It also explores the development of younger children's gait and then follows with an exploration of children's footwear. This chapter gives an overview of the known societal and biomechanical influences of children's footwear. Finally, this chapter introduces the thesis aims and provides an overview of subsequent chapters.

1.2 Background

Children's gait is commonly described or measured by quantitative measures. This can assist in understanding a number of different factors inclusive of age differences. and the differences in gait when children are shod versus unshod.

Toddlers and younger children under the age of 5 years, vary in their walking biomechanics compared to older children and adults. Typically developing toddlers usually progress out of the stiff infant standing posture within the first 4-5 months of walking experience and continue to progress toward an adult gait pattern. Given these differences in walking biomechanics, research on the gait patterns of older children cannot be compared to toddlers or children under the age of 5 years due to this gait immaturity. Therefore, this body of research was focused on children from when a child are steady on their feet (>2 years of age), prior to stabilisation of their gait to a more adult like pattern (>6 years of age).

1.2.1 The Gait Cycle

Children's gait is commonly described or measured by quantitative measures. This can assist in understanding a number of different factors inclusive of age differences and the differences in gait when children are shod versus unshod.

One full gait cycle is defined as the time from one foot making initial contact with the ground, to when the same foot again makes initial contact with the ground [1, 2]. This moves the body forward as one limb acts as a source of support, while the other limb advances forward. Each gait cycle is divided into two main phases: stance and swing phase. Stance phase is the term used when either foot is in contact with the ground, which accounts for around 60% of the gait cycle during walking [1]. Stance phase begins at heel strike or initial contact and ends when the big toe leaves the ground (toe off). Swing phase is the term used when the foot is lifted for limb advancement. Swing phase accounts for around 40% of the gait cycle during walking and begins when the foot is lifted from the ground (toe off) and continues until the next initial contact when the heel strikes the ground again [1]. Some evidence suggests that the swing phase of gait is under some degree of control by the neuromuscular system [3]. The duration of a gait cycle is divided into stance time and swing time with a period of time when both feet are in contact with the ground at the beginning and end of stance phase, known as double support time.

1.2.2 Spatiotemporal measures

There are a number of ways to measure gait parameters in children. These include biomechanical variables including spatiotemporal, kinematics, kinetics, electromyography and plantar pressure. Spatial (space) and temporal (time) measures of walking and running are commonly used methods to collect information and understand locomotion [4]. The GAITRite® Electronic Walkway (CIR Systems Inc. Havertwon, PA, USA) is often used in research to collect spatiotemporal outcome measures. The GAITRite technology is one of the simplest and most cost-effective methods used to research gait in children. The GAITRite has well-established reliability and validity compared to other gait measures and is well validated in the paediatric population [2, 5, 6]. Key gait measures in children vary with age. The key gait measures often described in children's gait research are summarised below (Table 1).

Table 1 Spatiotemporal measures and their definition

Spatiotemporal measures	**Definition**
Stride length (cm)	Measurement from the heel points of two consecutive steps of the same foot
Step length (cm)	Measurement of the heel points of two consecutive steps from one foot to the other
Toe in/out (degrees)	The angle between the middle of the steps and the middle of the foot
Step time (sec)	Time between the first contact of one foot to the first contact of the other foot
Stride time (sec)	Time between the first contact of one foot to the first contact of that foot again
Velocity (cm/sec)	The distance walked divided by the speed
Swing percentage (%)	Percentage of the gait cycle when the foot is not in contact with the ground
Stance percentage (%)	Percentage of the gait cycle with feet in contact with the ground
Double support time (sec)	Time during walking when both feet are on the ground
Cadence (steps/min)	Number of steps taken per minute

1.2.3 Development of gait patterns in younger children

The World Health Organisation describes typically developing children as those beginning independent walking between the ages of 8-18 months, walking at an average of 12.1 months of age [7]. Walking toddlers can cover more space more quickly and experience more visual input, compared to crawlers. Children can access, and play with more distant objects with walking, rather than what is on the floor in front of them. This fundamental skill also enables greater interaction with their care givers in a new and exciting way [8]. Some children learn to walk through different developmental stages. This is dependent on a number of different factors, including maturation of their central nervous system, sensory systems, muscle control and muscle strength.

While walking and running often appears easy to children, it is a complex and challenging development stage. Toddlers will often be less stable and less efficient in comparison to older children. The first indicators of gait are seen well before the onset of independent ambulation in the primitive walking patterns that can be elicited in newborns. These patterns are highly automated and reflect activity of central pattern generators which are located in the spinal cord [9]. Within the central nervous system, there are a number of changes that are essential for maturation of gait in children. These changes include an increase in motor cortex excitability, afferent feedback in ascending pathways [10, 11] and myelination of the corticospinal pathways [12]. Toddlers have a higher centre of gravity, low muscle to body weight ratio and immaturity of their central nervous and sensory systems. All of these factors contribute to an immature postural control and an unstable gait that is often seen in a child who has just started to walk independently [13, 14]. A younger child's visual, proprioceptive and vestibular systems all work together to assist a child in keeping their centre of gravity within their base of support, which generally occurs and functions well by six years of age [14].

Toddlers will begin to walk by adopting strategies to counteract their balance instabilities. They have mechanisms that assist them in adapting to this gait instability by changing their gait to assist in maintaining their balance until these systems mature further. They commonly do this through a wider base of support, shorter step length and a short swing phase [13]. Toddlers also lift their feet higher to assist with ground clearance during swing phase, in addition to keeping their arm guard high with a wide swinging motion [13, 15]. When toddlers begin to walk independently, with only a few weeks of practice they often begin to show signs of adult gait with pelvic rotation and synchronous arm swinging [13, 16].

Within the first 4-5 months of walking experience, toddlers generate forward mobility and progress out of the stiff infant standing posture by lowering their arms and narrowing their base of support. At around the age of 2-2.5 years old, or after 11-12 months after the onset of independent ambulation, a child begins to show a slightly more mature gait pattern [13]. This is demonstrated when a child narrows their base of support, shows a reciprocal and coordinated arm swing pattern with clear toe off and heel strikes during ambulation [13, 15].

Cadence and postural control continue to develop during walking over a 5 year period and walking velocity does not begin to stabilise until approximately 4 years of age (Sutherland). As a child's gait continues to mature, a pendulum style of gait becomes more apparent [17]. Confidence and refinement also enables an increase in velocity, step length and single support time and decreased cadence [6, 13]. Studies observing the gait of children aged between one to 10 years have found that normalized velocity and step length increases gradually from one to four years and stabilizes between five to 10 years [2, 18].

Skeletally, young children are different to adults. This is particularly observed at the foot and how it functions [19]. Young children are commonly more flexible, have a lower arch (or foot posture) [20] than older children and adults. During development, younger children's feet also go through a number of changes and structural adaptions that align with developmental stages such as growth rate, plasticity of the foot and gross motor development [21]. These rapid growth and development changes may be influenced somewhat by footwear worn during this time, however there is limited evidence in this area.

1.2.4 Children and Footwear

The global children's footwear market is estimated to be valued at $34.1 billion US [22] with aesthetics, foot growth rate in children and product innovation all fuelling the global market. Families often intuitively want to provide their children with the best shoe choices, however footwear knowledge can be a limiting factor [23]. Good foot health throughout childhood is often a concern for parents and health professionals [24]. The main areas of concern include if any external factors potentially influence foot development [25, 26]. In addition, questions of concern are often raised about what type (and when) children should start wearing footwear [27]. For health professionals, it is increasingly important to advance the knowledge around health literacy and to enhance the development of parents' knowledge of foot health information [23].

Advances in technology and social media platforms have influenced a parent opinion shift in access to health information. This influence can pose challenges for health professionals [28]. A recent qualitative study reported parents footwear choices and beliefs [29]. Parents valued well-fitting footwear and sought out recognised footwear companies. They believed this ensured their child had suitable and comfortable footwear. Parents had highly refined and entrenched beliefs of the importance of young children's foot health and its interface with footwear. These beliefs were heavily influenced by marketing from footwear companies, information on the internet, and health professionals [29].

Footwear plays a number of different roles for younger children. The primary role of footwear is providing protection from the environmental elements, to prevent pain or injury when in an outside environment [30]. Footwear is thought to provide a sense of safety, enabling children to interact with their environment. Free play is essential to build fundamental skills, assisting in development of gross motor skills enabling physical activity and overall health. There is little known about footwear and its impact on walking and running in younger children. Given the scale of the footwear industry and its impact, the author believes it is important to study these factors in young children.

1.3 Thesis overview

This thesis is presented in seven chapters with the overarching aim to explore the impact of footwear on younger children's walking and running. In the author's clinical practice, parents often seek advice about the best type of footwear for their young child. There is very limited information to guide recommendations. This clinical question prompted the body of research presented within this thesis.

1.4 Thesis aims

This thesis comprises of a systematic review of the literature (Chapter 2), methodology (Chapter 3) and three chapters (Chapters 4-6) addressing the following aims:

1. To determine what is the impact of shoe features on younger children's gait, and are there any differences between shoe sole flexibility compared to barefoot gait?
2. To determine what are the differences in spatiotemporal measures of gait between walking and running in three common types of children's footwear with a soft-soled shoe compared to barefoot in young children?
3. To determine what are the differences in spatiotemporal measures of gait of younger children wearing three different types of footwear with soft/flexible or stiffer soles?
4. To determine if muscle activity during walking and running in different types of footwear can be measured via surface EMG in younger children?

1.5 References Chapter 1

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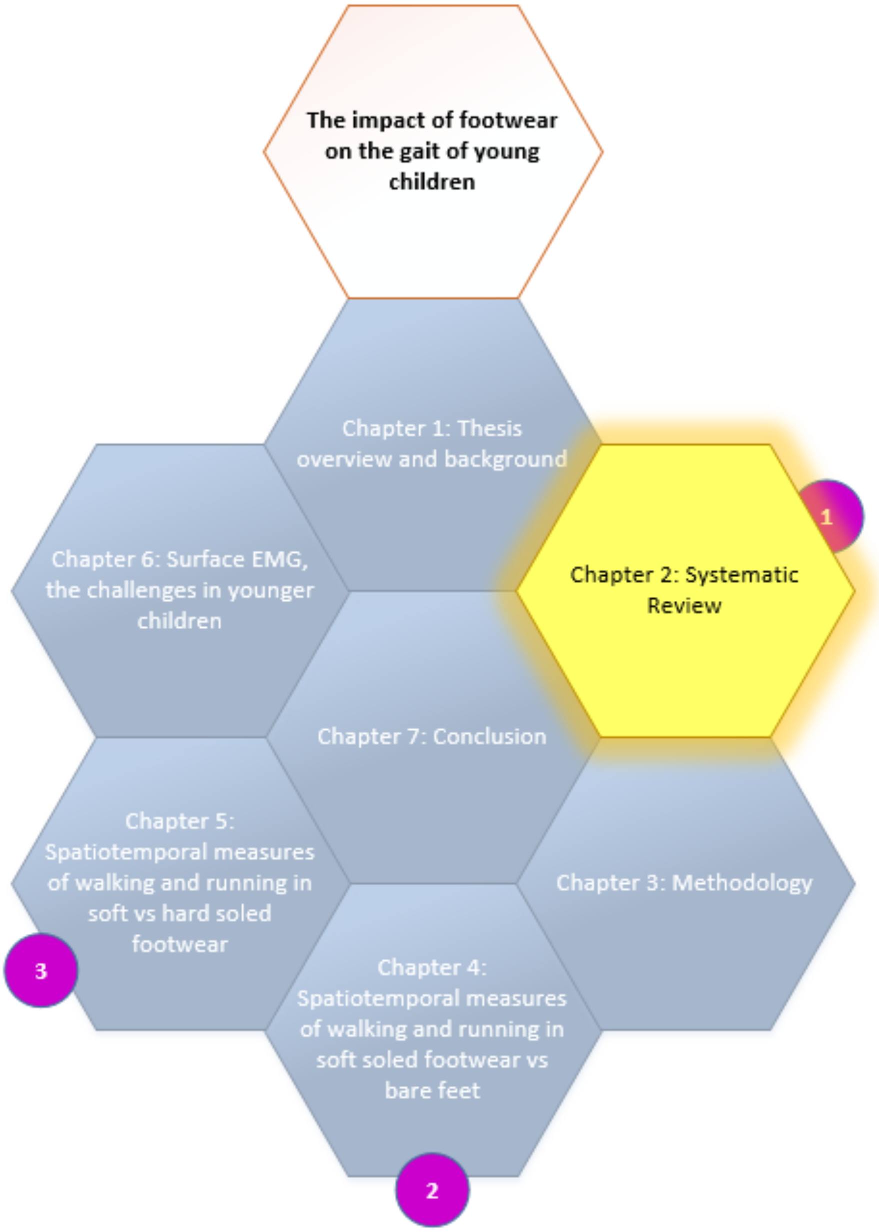
Chapter 2: Systematic Review

2.1 Preamble



As outlined in Chapter 1, there is limited evidence for the potential impact of footwear on children's gait. While there is some published evidence of the impact of footwear on the gait of children over the age of six, it is unclear how footwear impacts the gait of younger children, who have different gait to older children. This systematic review explored the scientific literature in this area, specific to young children. This chapter describes the current evidence exploring the impact of footwear with the aim to identify any impact of shoe features on younger children's gait. It also evaluated any differences between shoe sole flexibility compared to barefoot in younger children compared to children with established and sophisticated gait patterns.

2.2 Publication- Article 1

This article was published in the Journal of Foot and Ankle Research:

Cranage, S., Perraton, L., Bowles, KA. Williams C.M. The impact of shoe flexibility on gait, pressure and muscle activity of young children. A systematic review. *J Foot Ankle Res* **12,** 55 (2019). https://doi.org/10.1186/s13047-019-0365-7

2.3 Declaration for Thesis Chapter 2

In Chapter 2, the nature and extent of my contribution to the work was the following:

Nature of contribution	**Extent of contribution**
Author	70%

The following authors contributed to the work:

Name	**Nature of contribution**	**Extent of contribution**
A/Prof Cylie Williams	Co-author	10%
Dr. Kelly-Ann Bowles	Co-author	10%
Dr. Luke Perraton	Co-author	10%

Author contribution: All authors contributed to the review concept and design. SC extracted the data, SC, CMW and LP undertook the article reviews. SC and LP undertook the analysis and all authors contributed to the interpretation. The article was drafted by SC with revision of the article completed by CMW, LP and KB. All authors approved the version of the manuscript that has been published.

Declaration by co-authors:

The undersigned hereby certify that:

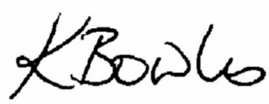
(1) The above declaration correctly reflects the nature and extent of the candidate's contribution to this work, and the nature of the contribution of each of the co-authors.

(2) They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;

(3) They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;

(4) There are no other authors of the publication according to these criteria;

(5) Potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit

Signature 1	A/Prof Cylie Williams 	Date: 02/12/2020
Signature 2	Dr. Kelly-Ann Bowles 	Date: 25/1/2021
Signature 3	Dr. Luke Perraton 	Date: 25/12/2020

2.4 Abstract

2.4.1Background

There is limited evidence of shoe impact in younger children, particularly in the context of immature gait patterns. It is unclear if the impact from shoes in younger children is similar to what has been seen in older children. This systematic review aims to identify any impact of shoe features on younger children's gait, and if there are any differences between shoe sole flexibility compared to barefoot.

2.4.2 Methods

Study inclusion criteria included: typically developing children aged ≤ 6 years; comparison of barefoot and shod conditions (walking and/or running) with shoe features or style of shoe described; sample size >1. Novelty types of footwear were excluded, as was any mention of in shoe support or modifications. Studies were located from six databases. Study methodology was assessed using the McMasters critical review form. Sample size weighted standardized mean differences (SMD) and 95% confidence intervals (CI) were calculated.

2.4.3 Results

Four studies were included. Participant age ranged from 15.2 to 78.7 months, with 262 participants across all studies. All studies had limited methodological bias based on their design type. Compared to barefoot walking, shoes increased velocity, step time and step length. Shod walking decreased cadence. Peak plantar pressure was generally lower in the stiff shoe design and there was a higher peak plantar pressure in the Ultraflex shoes. No studies were found investigating muscle activation.

2.4.4 Conclusions

Shoes affect younger children's gait in spatiotemporal gait aspects, similar to those seen in older children. There is limited evidence on effects of particular shoe features such as sole hardness, on gait, and no evidence of any changes in muscle activation patterns. Further research is required to evaluate the impact of different types of shoe and shoe features in this population to provide clinical advice on the type of shoe that is appropriate in this age group.

Keywords: Shoes, footwear, gait, child, toddler, walk, run

2.5 Background

Mature gait patterns are well established in children by the age of 3 years (1). Typical indicators of the establishment of mature gait include the presence of a reciprocal arm swing and heel strike. There is also an increase in velocity, step length and single support together with a reduction in cadence (1). Studies observing the gait of children between the ages of 1 to 10 years have found that normalised velocity and step length increases gradually from 1 to 4 years and stabilises between 5 to 10 years of age (2). Young children's walking and running is often less stable and less efficient than that of older children and adults due to a higher centre of gravity; lower muscle to body weight ratio; an immature nervous system and poorer postural control (1).

Health professionals and members of the public often advise parents to allow their toddlers to be barefoot as much as possible, or to wear soft soled shoes in the early developmental stages of walking (3). This is thought to allow an increase in muscle strength in their feet and to assist in sensory experiences with different surfaces. Health professionals and shoe manufacturers often give advice based on the assumption that a shoe should not affect normal foot function or motor development in younger children and therefore be as close to barefoot walking as possible (3). However, there is limited research evidence to guide these shoe recommendations in younger children.

There is also limited research to guide health professionals on the impact of shoes on the gait of children. This is predominantly in children over the ages of six years (4). Older children walking in shoes resulted in an increased walking velocity, longer stride length, increased stride time, decreased cadence, wider base of support, later toe off time during the gait cycle, increased double support time and a longer stance time, than when walking barefoot (5).

There has also been an observation of changes in lower limb kinetics with shoes changing tibialis anterior activity (compared to barefoot in children with a mean age of 7.7 years (range 2-15 years) (6). In another study, shoes were also noted to decrease the intrinsic motion of the foot, which could indicate possible splinting effect of shoes on foot joints, a study undertaken with children aged above six years (7).

There is limited available evidence on shoe impacts in younger children, particularly in the context of an immature gait pattern. It is particularly unclear if there are similar impacts from shoes in younger children as seen in their older counterparts. The primary aim of this systematic review was to examine the impact of shoe features on younger children's gait. The secondary aim was to investigate any differences between shoe sole flexibility compared to barefoot gait.

2.6 Method

2.6.1 Search strategy

This review was undertaken in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (8). Two reviewers (SC, CW) examined six databases from inception to April 2018. Databases searched were: OVID Medline, EMBASE, CINAHL, EBM reviews, AMED and Sports Discus. Search terms included synonyms of: child, infant, pediatric, gait, walk, jog, run, ambulation stride, step, swing, pressure, force, kinematics, kinetics, angle, spatiotemporal, EMG, electromyography, gait, GAITRite, Trigno, footwear, shoe$, trainer$, sole, boot$, sandal$, stiffness, hardness, Velcro, buckle, lace, fasten* (Limiter for full text publications and human studies). Boolean operators "AND" and "OR" were used to combine search terms relating to the search question. Where search term variations existed, truncation (*) was used. All research designs were included. An example search strategy for Ovid Medline is outlined (Figure 1). Studies were only included if they were published in a peer reviewed journal.

1.	Child
2.	Infant
3.	P(a)ediatric
4.	Walk
5.	Jog
6.	Run
7.	Ambula[te]tion
8.	Stride
9.	Step
10.	Swing
11.	Pressure
12.	Force
13.	Kinematic$
14.	Spatiotemporal
15.	Electromyography
16.	Gait
17.	Trigno
18.	Footwear
19.	Trainer$
20.	Sole
21.	Boot$
22.	Sandal$
23.	Stiff*
24.	Hard*
25.	Velcro
26.	Buckle
27.	Lace
28.	Fasten*
29.	1 or 2 or 3
30.	4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17
31.	18 or 19 or 20 or 21 or 22 or 23 or 24 or 25 or 26 or 27 or 28
32.	29 and 30 and 31
33.	Limit 32 to human

Figure 1 Search Strategy Ovid Medline

2.6.2 Eligibility criteria and screening

Prior to searching, the research team determined inclusion and exclusion criteria for the study (Table 2). Duplicates were removed from the search yield via Endnote and two authors (SC and CW) independently screened the abstracts of all retrieved studies against the eligibility criteria using Covidence (9). Articles were included for full text review where there was uncertainty from the abstract.

Table 2 Eligibility criteria

Inclusion criteria	Exclusion criteria
Children aged ≤ 6 years	Articles with full text not published in English
Comparison of barefoot and shod conditions (walking and/or running)	Novelty types of footwear
Typically developing children	Orthoses, arch supports or innersoles mentioned
No identified pathology known to impact on gait	Children having a medical condition known to impact on gait
Sample size of total participants > 1	
Shoe features or style described	

Two authors reviewed the title and abstract (SC, CW) to determine if the study was to be included in a full text screening. Any differing opinions were discussed and resolved in person. In cases of non-consensus, a third author's opinion was planned for consultation; however, this was not required. All citations of included articles and reference lists were also screened against the eligibility criteria and any articles meeting the inclusion criteria were also included within this review.

2.6.3 Risk of bias assessment

All articles included within the final review underwent methodological assessment using the McMaster critical review form- Quantitative studies (10) which is applicable to Randomised Controlled Trials, controlled trials and cross sectional intervention trials. The tool has fifteen individual assessment points within eight domains. Risk of bias was completed independently by two reviewers (SC and LP) and achieved consensus with further discussions and review from a third and fourth reviewer where required (CW, KB).

2.6.4 Data management

Where data suitable for extraction was not available, authors were contacted to provide unpublished data. If there was no response within 4 weeks, these articles were excluded from the final review. Data describing the study sample characteristics; study design; shoe design and features; spatiotemporal measures; and kinetics were extracted by two reviewers independently. Consensus on results was discussed between two reviewers who extracted the data (LP and SC). Means and standard deviations for each group were extracted where data was provided or supplied on request.

2.6.5 Statistical methods

Participant characteristics were described by means, standard deviations (SD) and frequencies (%). Data were extracted from each study by age, and where there was greater than one participant per age and per condition gait variables were included for meta-analysis. To satisfy the assumption of independence only the data from right side were used within meta-analysis (11). Where only means and confidence intervals were reported, the group standard deviations were calculated as per the formula $SD = \sqrt{N} \times (\text{upper limit} - \text{lower limit})/3.92$. Sample size weighted standardized mean differences (SMD) and 95% confidence intervals (CI) for gait variables were calculated using Stata 13 (StataCorp LP.) with the differences in mean scores between the shoe groups and the mean standard deviation using a random effect model (Mantel-Haenszel method) to account for the use of paired data. SMDs were considered to be statistically significant if their associated CI did not cross zero. Interpretations of strength of the SMDs statistics were based on Cohen's guidelines with small effect ≥0.2, medium effect ≥0.5, and large effect ≥0.8 (12).

2.7 Results

2.7.1 Study selection and design

A total of 4037 articles were screened by two independent reviewers (SC, CW). Thirty two studies were included for full text screening based on the eligibility criteria. Five studies met the inclusion criteria and were included in the final review. The search and selection process of the articles is described in Figure 2.

One study was subsequently excluded, as the data were only aggregate data reported for children between five to 11 years (13). Gait variables for the five and six year old children within this paper were unable to be separated from the data of children aged seven and above. The author was contacted however no response was received.

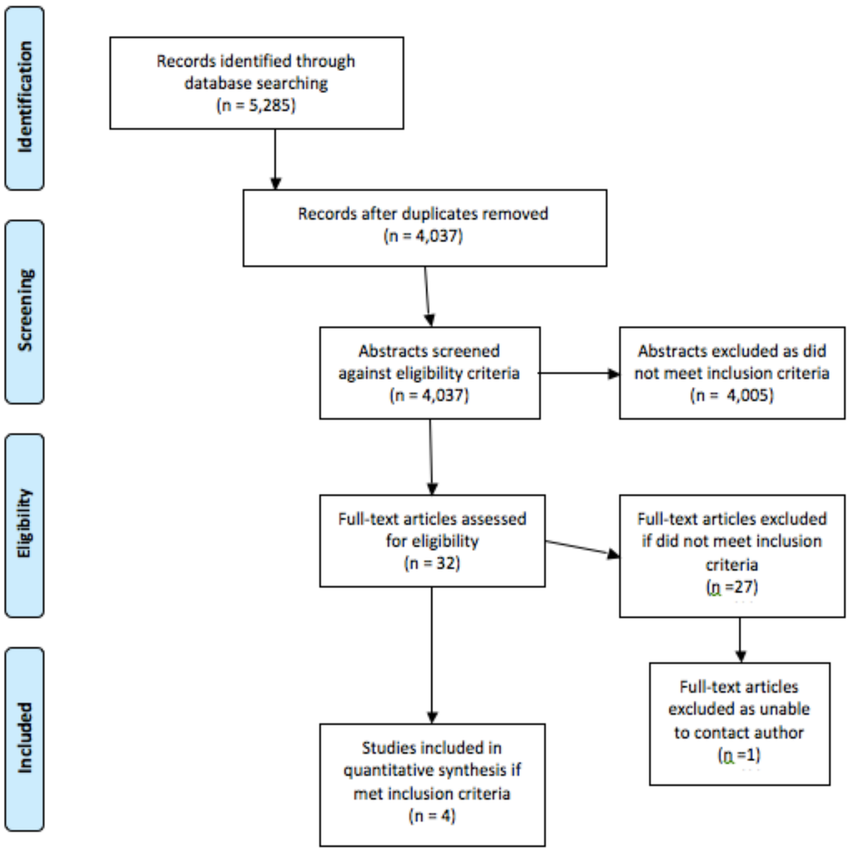


Figure 2 PRISMA Diagram

2.7.2 Characteristics of Included Studies

Table 3 includes the characteristics of the four included papers. All were cross sectional studies (Level IV evidence on the NHMRC evidence hierarchy). The age of the participants in the included studies ranged from 15.2 months to 78.7 months and there were a total 262 participants in the four studies. Table 3 also provides the gait variables per age and per condition.

Table 3 Description and methodological approach of studies included in review

Author	**Country**	**Design**	**Sample size**	**Gender** (Female) n (%)	Mean age (SD)months	**Gait type**	**Shoe conditions included in analysis**	**Outcome measures**
Buckland, 2014	USA	Cross sectional Repeated measures	25	8 (32%)	15.2 (2.0)	Walk	Lace up sneakers (Ultraflex, Medflex, Lowflex, Stiff)	Spatiotemporal
Hillstrom, 2013	USA	Cross sectional Repeated measures	24	8 (32%)	15.2 (2.0)	Walk	Lace up sneakers (Ultraflex, Medflex, Lowflex, Stiff)	Plantar pressures
Lythgo, 2009	Australia	Cross sectional Repeated measures	69 (5 years) 140 (6 years)	33 (48%) 75 (54%)	68.4 (0.2) 78.7 (0.3)	Walk Walk	Athletic shoes/runners (own)	Spatiotemporal
Kennedy, 2018	Australia	Cross sectional Repeated measures	1 (4 years) 3 (5 years)	0 (0%) 2 (67%)	50.9 62.8 (5.16)	Walk	Optimal (runners) own shoes/sub optimal (flip flops) own shoes	Spatiotemporal

There were three studies examining the spatiotemporal features of gait (5, 14, 15) and one that investigated pressure (16). There were no studies found that investigated muscle activity. All four included studies examined gait while the young children wore athletic type shoes and compared gait in these to barefoot. Two studies, with the same cohort of participants, standardized the torsional flexibility of the shoes (14, 16). The torsional flexibility was assessed by determining the amount of force required to cause angular rotation on each shoe, and results classified shoes into; Ultraflex, Medflex, Lowflex and stiff (14, 16). One of these two studies evaluated spatiotemporal measures during walking (14), while one study evaluated plantar pressures during walking (16) and reported the data on the same cohort of children. Running was not assessed in any of the included studies.

2.7.3 Spatiotemporal findings

There were three studies that reported spatiotemporal changes for barefoot versus shoes (Table 4). Two studies had data available for similar ages and were used within a meta-analysis for the variables velocity, cadence, step time and step length (Figures 3–6). Compared to barefoot walking, shoes decreased cadence (SMD= -2.50, 95%CI=-3.45,-1.54, I^2=87.2%), increased step time (SMD 1.44, 95%CI=-0.04, 2.91, I^2=95.8%increased step length (SMD=5.60, 95%CI=4.66, 6.55, I^2=66.4%) and may increase velocity, (SMD=1.65, 95%CI=0.74, 2.56, I^2=89.9%).

Table 4 Velocity, cadence, step time and step length data included within meta-analysis

Author	Mean (SD) Age month	Conditions	Velocity mean (SD), cm/sec)	Cadence mean (SD), steps/min	Step Time (cm/sec) Right only	Step length (cm) Right only
Buckland, 2014	15.2 (2.0)	Barefoot	87.30 (19.70)			26.30 (4.30)
Buckland, 2014	15.2 (2.0)	Lace up sneakers (Ultraflex)	87.70 (18.90)			28.10 (3.70)
Buckland, 2014	15.2 (2.0)	Lace up sneakers (Medflex)	85.70			28.10 (5.70)
Buckland, 2014	15.2 (2.0)	Lace up sneakers (Lowflex)	83.10 (19.30)			27.40 (4.40)
Buckland, 2014	15.2 (2.0)	Lace up sneakers (Stiff)	86.00 (16.20)			28.10 (3.70)
Lythgo, 2009	68.4 (0.2)	Barefoot	124.80 (4.60)	152.60 (4.10)	389 (11)	48.70 (1.10)
Lythgo, 2009	78.7 (0.3)	Barefoot	127.5 (2.40)	146.30 (2.60)	415 (8)	52.20 (0.90)
Lythgo, 2009	68.4 (0.2)	Athletic shoes/runners (own)	130.30 (4.20)	142.80 (3.40)	423 (10)	54.80 (1.20)
Lythgo, 2009	78.7 (0.3)	Athletic shoes/runners (own)	133.50 (2.80)	138.40 (2.10)	437 (10)	57.80 (0.90)
Kennedy, 2018	50.9	Barefoot	114.8	157.1	378	44.23
Kennedy, 2018	66.8 (5.1)	Barefoot	113.7 (14.3)	147.5 (15.8)	410 (45.1)	46.38 (1.3)
Kennedy, 2018	50.9	Optimal (runners)	139.9	158.3	377	53.23
Kennedy, 2018	66.8 (5.1)	Optimal (runners)	126.0 (9.6)	140.4 (14.6)	430 (42.7)	54.42 (2.8)

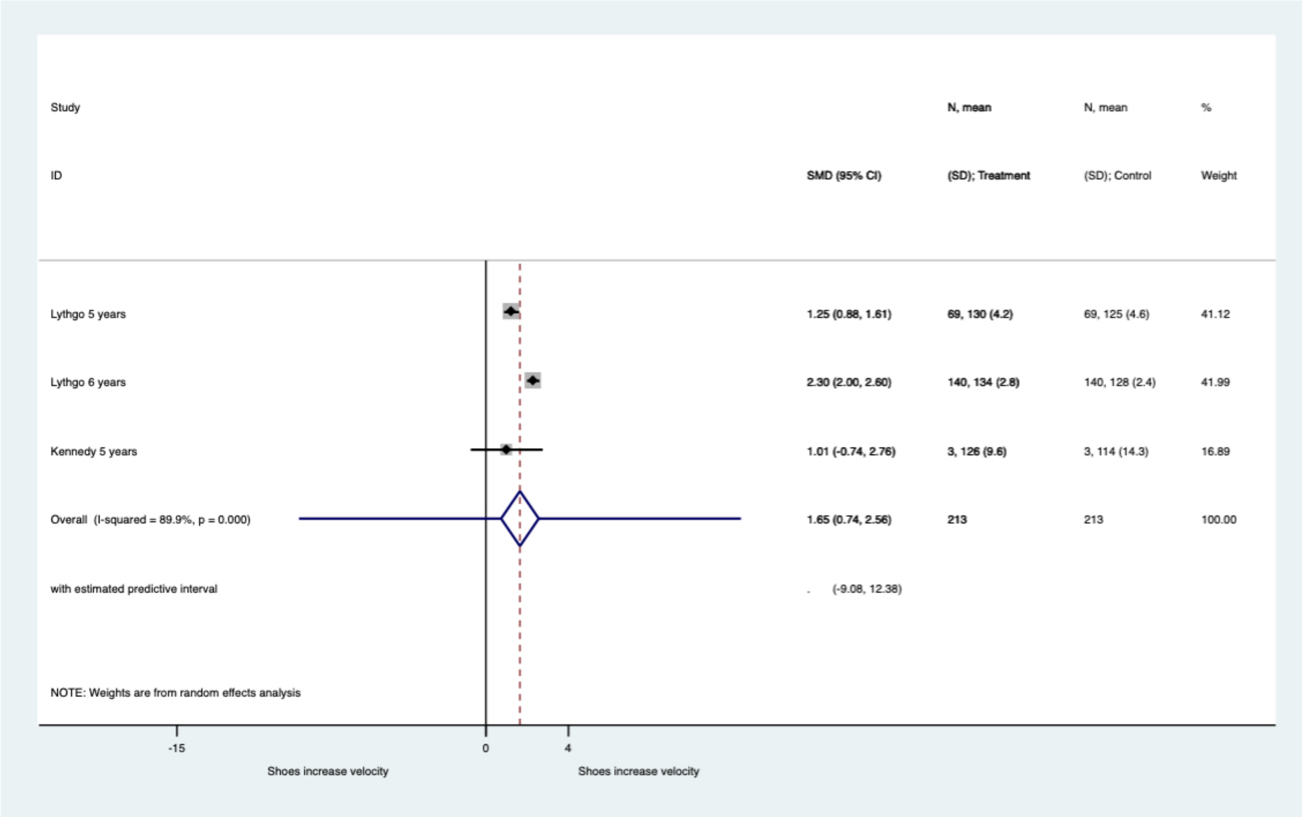


Figure 3 Forest plot of the differences in velocity between shoes compared to barefoot walking for young children

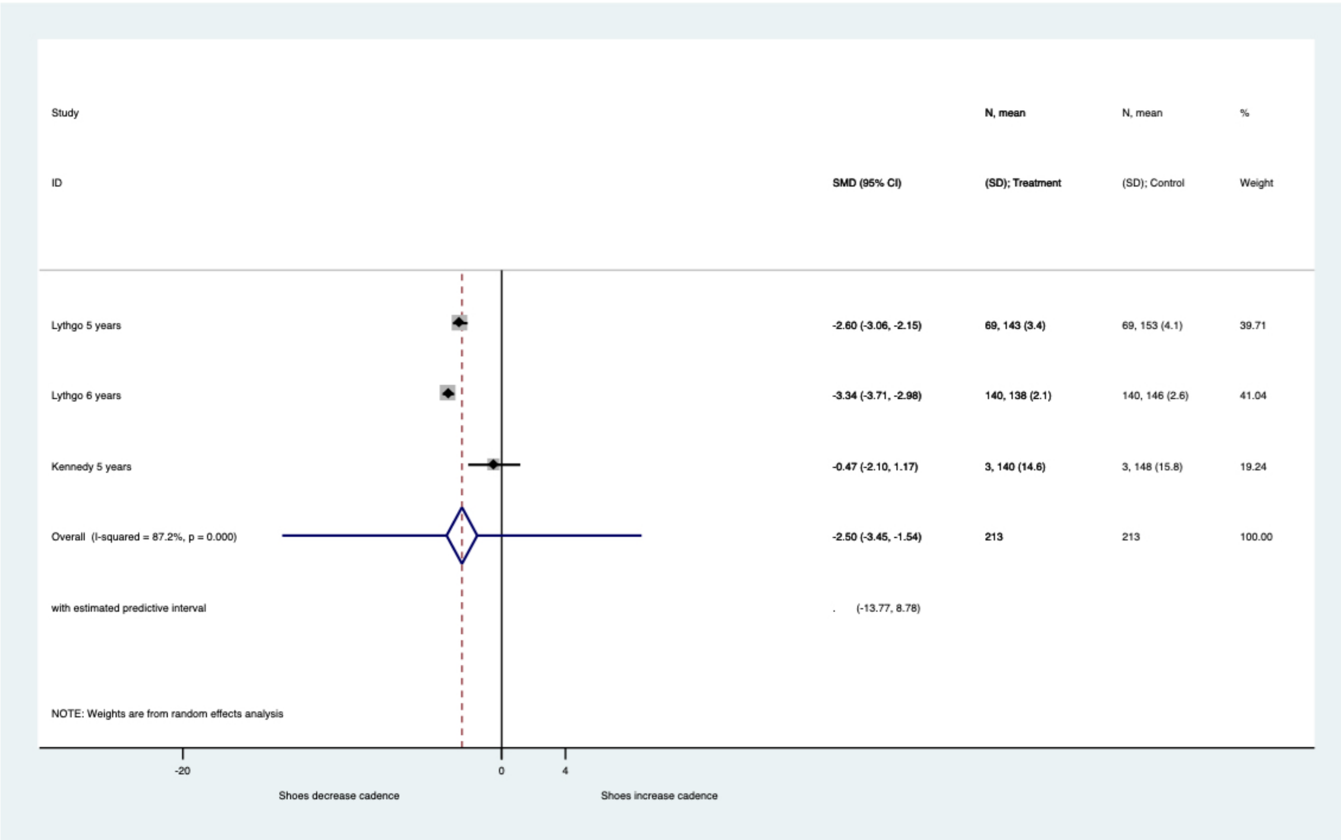


Figure 4 Forest plot of the differences in cadence between shoes compared to barefoot walking for young children

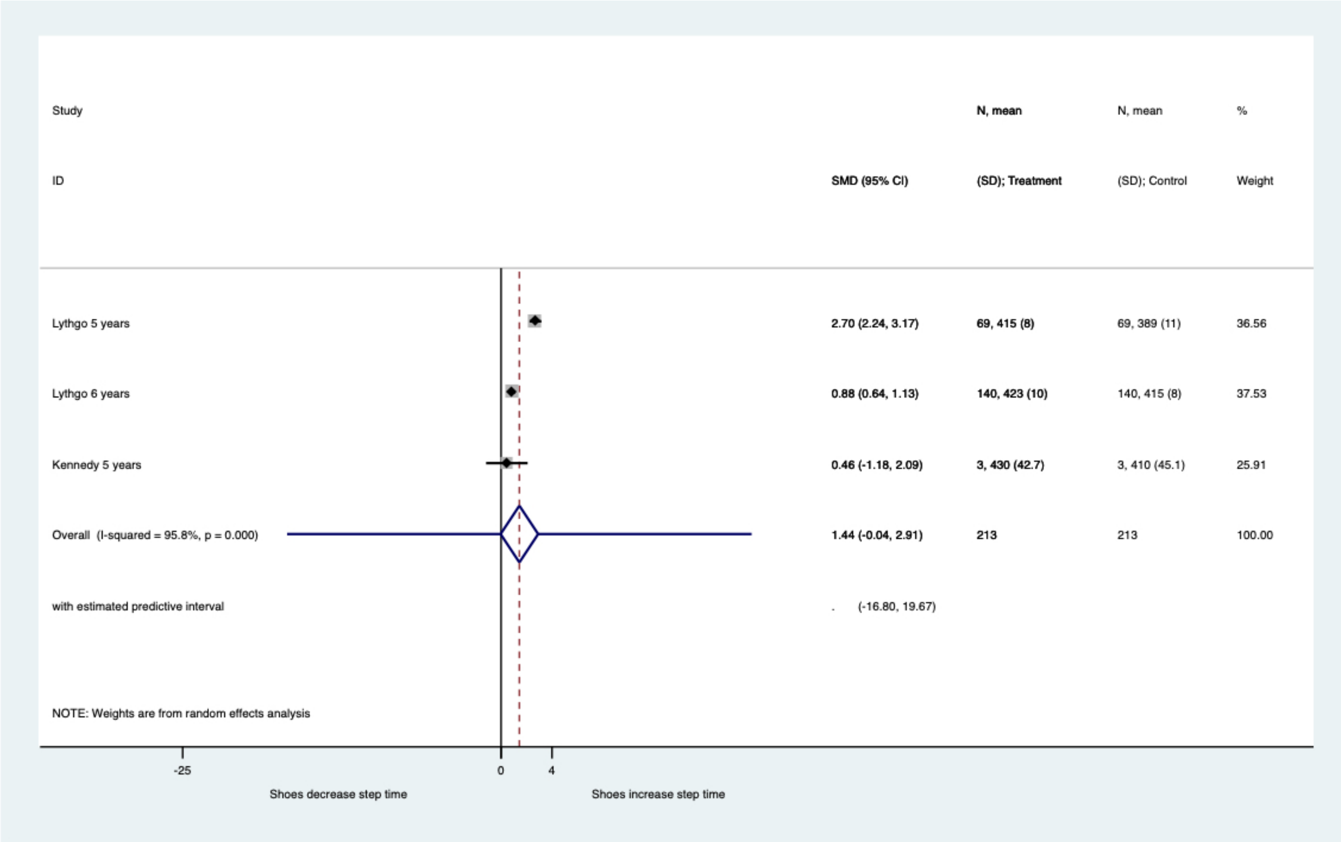


Figure 5 Forest plot of the differences in step time between shoes compared to barefoot walking for young children

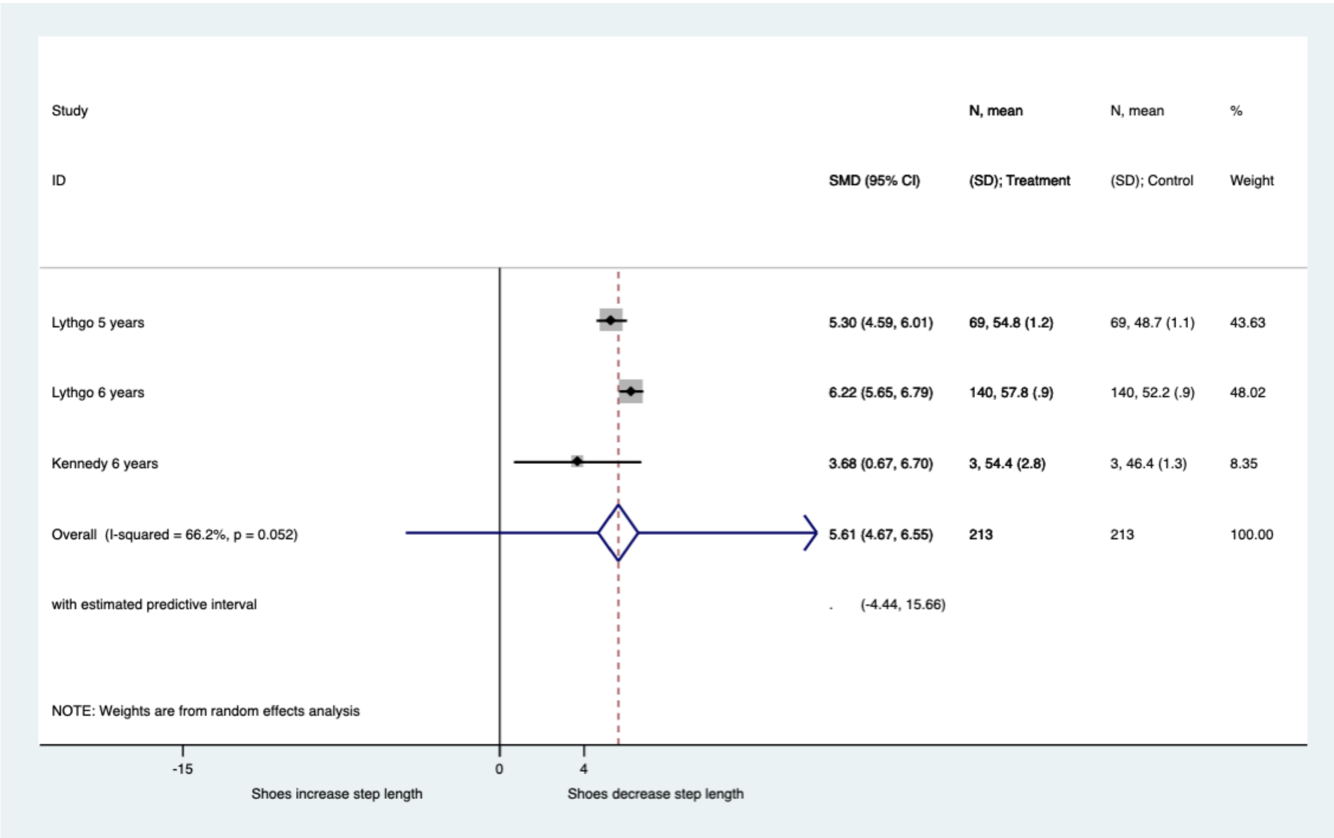


Figure 6 Forest plot of the differences in step length differences between shoes compared to barefoot walking for young children

2.7.4 Plantar pressures

Peak plantar pressures were significantly different across four differing shoe conditions relating to stiffness of shoe sole (16). Overall, the peak plantar pressure was generally lowest in the stiff shoe design (mean= 9.6, SD=3.2N/cm2) and there was a higher peak plantar pressure in the Ultraflex shoes (mean= 13.0, SD= 3.8 N/cm2). This was the only study that examined pressure variables (16).

2.7.5 Study Quality (risk of bias assessment)

A quality assessment of the articles was completed to assess the risk of bias with the McMaster quantitative critical appraisal tool (10). All domains were scored for each of the included articles (Table 5). Three studies did not provide a justification of their sample size (14-16). The clinical importance and clinically meaningful difference between groups were unable to be concluded due to low power within one study (14). All of the studies included within the review showed good methodology quality for their design type.

Table 5 Methodological quality of the studies included in the review as assessed by the McMasters Quality Assessment

Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Score
Buckland (14)	1	1	1	0	1	1	1	1	1	1	1	0	0	1	1	12/15
Hillstrom(16)	1	1	1	0	1	1	1	1	1	1	1	0	0	1	1	12/15
Lythgo (5)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	15/15
Kennedy (15)	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	14/15

2.8 Discussion

The findings of this systematic review are the first to examine the impact of shoes on young children. The previous systematic review of children between the ages of 1.6 years and 15 years found that children wearing shoes walk faster by taking longer steps, with an increase in the support phases of the gait cycle (4). These gait changes may result from footwear increasing the leg length related to the shoe, or an increased mass of the shoe increasing inertia of the leg during the swing phase (4). The gait changes observed in older children were similar to those observed in younger children within this systematic review. Given the lightweight nature and low shoe base to upper ratio of young children's shoes, it is unknown if shoe height and mass also contribute to these changes in younger children's gait.

The variability of shoe advice from health professionals may be challenging for parents (17, 18). Previous studies have described optimum foot development occurring in a barefoot environment with the primary role of shoes being to protect the foot from injury (3). The results from this systematic review indicate there is an absence of evidence to support one shoe type over another, and limited evidence that shoe flexibility has an impact on young children's gait. While shoes appear to have some influence on gait parameters, it is not yet known if these changes effect function or have any long-term effects on foot health. There are also consistent messages to parents that a stiff and compressive shoe may cause deformity, weakness and loss of mobility (3). In spite of these negative messages, there are no consistent international and evidence-based recommendations to guide clinicians or manufacturers on the optimal shoe for younger children, in particular whether a child should wear a soft or hard-soled shoe. It is unfortunate that the results of this review indicate that more research is needed rather than providing credible evidence to support either of these recommendations.

This absence of evidence supporting shoe recommendations for children is also a challenge when clinicians are presented with children who have a pathological gait or a foot or lower limb concern. If there is limited literature on typically developing children and shoes, it is difficult to compare the impact of shoes on children with pathological gait. The findings of this review will hopefully encourage future research into the effects of shoe sole features on the gait parameters in children; therefore helping to guide clinicians and shoe industries on the appropriate shoe for younger children.

There are a number of limitations within this review including the limited number of available studies for analysis. It is unknown if the lack of studies is correlated to the challenges that present while testing this age group of children. The psychosocial challenges of having children within a gait laboratory environment is proposed as a large contributing factor to the limited number of studies available to base this review on.

Often gait analysis methods rely on placing markers on small children, which potentially can cause the child to subtly change gait, particularly in young children. The gait environment is also an unappealing play environment therefore challenging to provide ongoing motivation for a younger child to complete all tasks in order to obtain a complete data set during testing.

There was also a limitation in the variability of the shoe and limited descriptions. Like adults, young children wear a variety of shoes including athletic shoes, sandals or boots. It is unknown if the variation in shoe type and their features also contribute to the differences in gait. An additional limitation is the limited number of studies included within the meta-analysis. One of the included studies had a small sample size of four participants for the age range we were interested in (15), therefore, caution should be applied to these results. All full text articles were limited to English which is another limitation of this study.

Further research is required for health professionals to provide recommendations on the optimal shoe characteristics for younger children, including sole hardness. Prospective research is required to determine whether shoe and sole flexibility lead to changes in kinetics, kinematics and muscle activation patterns in younger children and whether changes associated with shoes are associated with clinical and patient-reported outcomes.

2.9 Conclusion

Shoes affect the gait of young children by increasing velocity, cadence, step time and step length compared to bare feet, similar to that of older children. There is limited evidence on the effect of particular shoe features such as sole hardness, on gait and no evidence on any changes in muscle activation patterns. Further research is required to evaluate the impact of different types of shoe and shoe features in this population to provide clinical advice on the type of shoe that is appropriate in this age group.

2.10 Declarations

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and material: Please contact author for data requests

Competing interests: The authors declare that they have no competing interests

Funding: SC is supported through an Australian Government Research Training Program Scholarship. CMW is support by a National Health and Medical Research Council Early Career Health Research Professional Fellowship. This research did not receive any funding.

Author contribution: All authors contributed to the review concept and design. SC extracted the data, SC, CMW and LP undertook the article reviews. SC and LP undertook the analysis and all authors contributed to the interpretation. The article was drafted by SC with revision of the article completed by CW, LP and KB.

Acknowledgements: Not applicable

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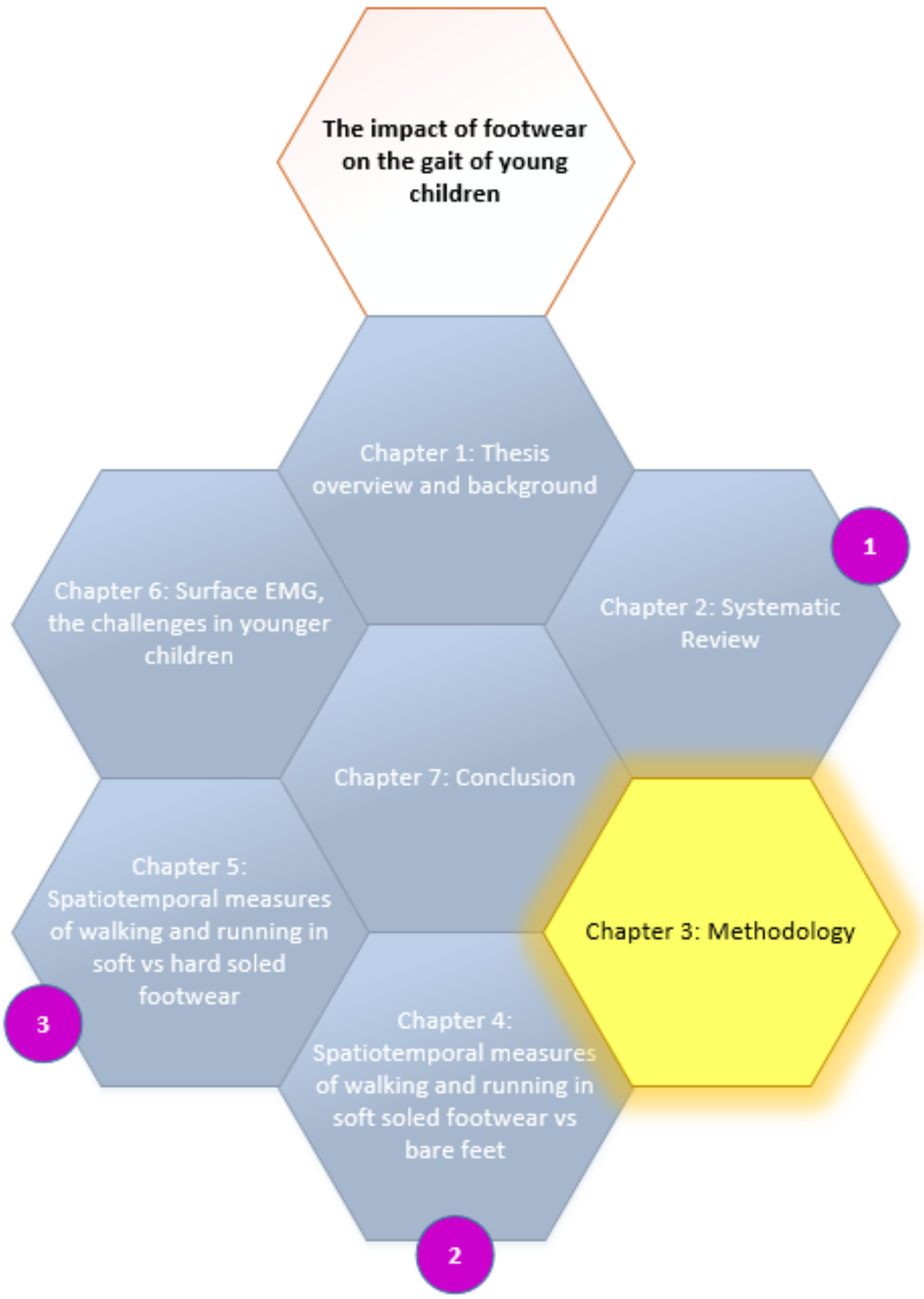
Chapter 3: Methodology

3.1 Preamble



This chapter provides in depth methodology used in this research design, as the "included published works" format does limit the level of detail in the following chapters. This chapter aims to provide greater context for subsequent chapters focusing on gait analysis outcomes with different footwear types. It highlights the techniques used during data collection for both gait and anthropometric measures. It also describes the room set up and the reward system that was used for the gait analysis in young children. Methodology of data analysis is included within subsequent chapters.

3.2 Ethics and Trial registration

The Human Research Ethics Committee of Monash University, Victoria, Australia, approved this research (HREC/17/8549) (Appendix 1). The study protocol was registered on the Australian and New Zealand Clinical Trial Registry (ANZCTR12617000999336) (Appendix 2).

3.3 Study design

A quasi-experimental design was used for the study. Intervention (barefoot and footwear) conditions were randomised using a Latin square randomisation method (Figure 7). This randomisation method was chosen to account for fatigue in the participants throughout the trials.

Testing conditions included:

Condition 1 – Barefoot walking at self-selected pace

Condition 2 – Barefoot running at self-selected pace

Condition 3 – Self-selected paced walking in sneaker style footwear

Condition 4 – Self-selected paced running in sneaker style footwear

Condition 5 – Self-selected paced walking in boot style footwear

Condition 6 – Self-selected paced running in boot style footwear

Condition 7 – Self-selected paced walking in sandal style footwear

Participant	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6	Condition 7
213	Barefoot	Sandal (Hard)	Sandal (Soft)	Runner (Hard)	Runner (Soft)	Boot (Hard)	Boot (Soft)
203	Sandal (Hard)	Sandal (Soft)	Runner (Hard)	Runner (Soft)	Boot (Hard)	Boot (Soft)	Barefoot
207	Sandal (Soft)	Runner (Hard)	Runner (Soft)	Boot (Hard)	Boot (Soft)	Barefoot	Sandal (Hard)
212	Runner (Hard)	Runner (Soft)	Boot (Hard)	Boot (Soft)	Barefoot	Sandal (Hard)	Sandal (Soft)
206	Runner (Soft)	Boot (Hard)	Boot (Soft)	Barefoot	Sandal (Hard)	Sandal (Soft)	Runner (Hard)
204	Boot (Hard)	Boot (Soft)	Barefoot	Sandal (Hard)	Sandal (Soft)	Runner (Hard)	Runner (Soft)
205	Boot (Soft)	Barefoot	Sandal (Hard)	Sandal (Soft)	Runner (Hard)	Runner (Soft)	Boot (Hard)
208	Barefoot	Sandal (Hard)	Sandal (Soft)	Runner (Hard)	Runner (Soft)	Boot (Hard)	Boot (Soft)
209	Sandal (Hard)	Sandal (Soft)	Runner (Hard)	Runner (Soft)	Boot (Hard)	Boot (Soft)	Barefoot
201	Sandal (Soft)	Runner (Hard)	Runner (Soft)	Boot (Hard)	Boot (Soft)	Barefoot	Sandal (Hard)
202	Runner (Hard)	Runner (Soft)	Boot (Hard)	Boot (Soft)	Barefoot	Sandal (Hard)	Sandal (Soft)
214	Runner (Soft)	Boot (Hard)	Boot (Soft)	Barefoot	Sandal (Hard)	Sandal (Soft)	Runner (Hard)
215	Boot (Hard)	Boot (Soft)	Barefoot	Sandal (Hard)	Sandal (Soft)	Runner (Hard)	Runner (Soft)
211	Boot (Soft)	Barefoot	Sandal (Hard)	Sandal (Soft)	Runner (hard)	Runner (Soft)	Boot (Hard)
210	Barefoot	Sandal (Hard)	Sandal (Soft)	Runner (Hard)	Runner (Soft)	Boot (Hard)	Boot (Soft)

Figure 7 Randomisation sequence

3.4 Participants and setting

Participants were aged between two and four years, with no medical conditions known to impact gait, and this was based on parent report, supported with the collected anthropometric measures. Participants were recruited during one week of advertising through social media (Facebook, Twitter), and university newsletters flyers (Figure 8). All children who participated in the study had written parental consent (Appendix 3), and where possible, children provided verbal assent. Data were collected at a temporary gait laboratory set up at Monash University (Figure 9).

Figure 8 Flyer used for participant recruitment

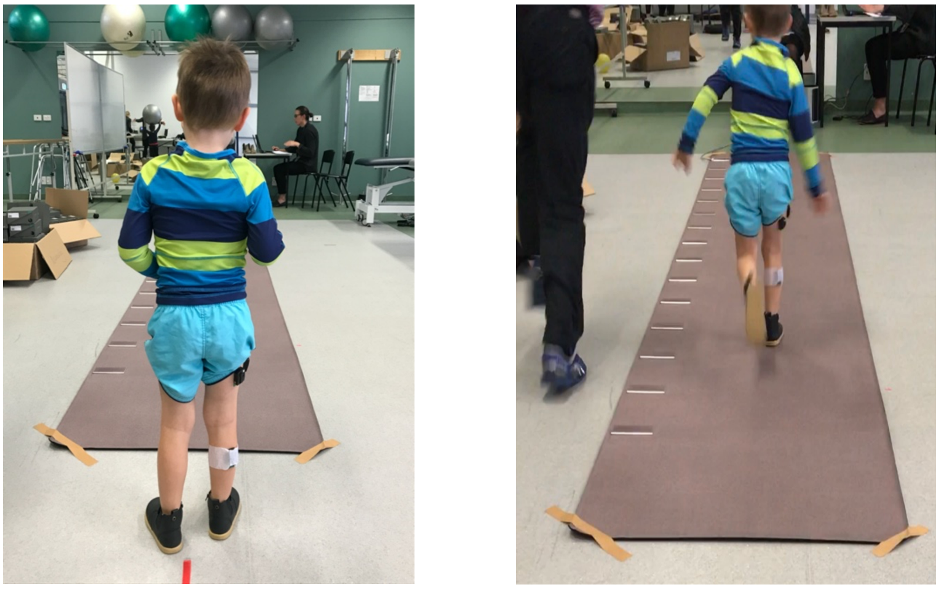


Figure 9 Temporary gait lab set up Monash University

3.5 Measures and outcomes

Anthropometric data was collected from every child at the start of the testing session. Parents provided the child's age (in years), gender, and footwear size (European shoe size) as measured on the footwear supplier's website (Appendix 4). The research team collected height (cm) using a stadiometer (Seca, Hamburg, Germany); weight (Kg) using a calibrated digital scale (Anko Electronics, California, USA) and calculated body mass index (Kg/m^2) from these measures. All measures were taken in line with the manufacturer's guidelines. For weight, the scales were places on a flat concrete surface and calibrated prior to use. Foot and lower limb data (ankle dorsiflexion, Foot Posture Index-6, and isometric muscle strength) were collected to compare the measures of participants to published normative measures of the same age group [2-5].

3.5.1 Ankle dorsiflexion

Ankle dorsiflexion range of motion was measured using a weight bearing ankle lunge with the leg straight and then with the knee bent [6], using a digital inclinometer (Laser Depot, Adelaide, Australia) (Figure 10). Prior to measurement, the dynamometer was placed with its long axis on a flat surface beside the child's foot and calibrated to 0°. The child placed their hands on the wall on front of their body, shoulder width apart. The right leg was placed behind them as far as they could, and parallel to the opposite leg, while keeping their heel flat on the ground. The researcher completing the measurement for all children assisted the child to slowly move their foot back, until they were able to hold a lunge position with the heel on the floor, the right foot straight, and perpendicular to the wall to minimise the amount of subtalar joint pronation. This was then repeated with the knee bent. The digital inclinometer was placed approximately one centimetre superior to the posterior calcaneal tuberosity. All measures were completed on the right side only, as previous literature has reported a high correlation between left and right measures in non-pathological populations [7]. This method of measurement has been used in a number of studies with children [2, 6] and has high inter and intra-rater reliability [8].

Figure 10 Digital inclinometer

3.5.2 Foot Posture Index-6

Static foot posture was measured using the Foot Posture Index-6 (FPI-6) [5]. The foot posture index has international normative reference data for foot posture across childhood [3]. The FPI-6 uses a six-item criterion based on observations of the rearfoot and forefoot in a participant who is standing in a relaxed position. The rearfoot is assessed via palpation of the head of the talus, observation of the curves above and below the lateral malleoli and the amount of inversion/eversion of the calcaneus. The forefoot observations quantify the bulging of the talonavicular joint, congruence of the medial longitudinal arch and the amount of abduction/adduction of the forefoot on the rearfoot. Each of the six items is scored between -2 and +2. The FPI-6 score may range from -12 (highly supinated) to +12 (highly pronated) using a standard protocol [5]. Normative values of foot posture index have been studied in children aged 3 years and above [3].

3.5.3 Isometric muscle strength

Isometric muscle strength of the knee extensors (quadriceps), knee flexors (hamstrings) and ankle plantarflexors were quantified using a Lafayette hand-held dynamometer (Figure 11). Testing was conducted following a modified standardised protocol shown to be reliable in children for ankle strength measures [1]. As strength was not a primary outcome of this study, modified assessment was completed at times due to the younger age of the children to determine any strength deficits for exclusion in the study. For ankle plantarflexion, the child was seated, looking straight ahead with the hips flexed and the knees comfortably extended. The hands were resting on the thighs with the heels positioned over the edge of the table. The lower limb was stabilised just proximal to the ankle joint. The dynamometer was placed against the plantar surface of the foot, just proximal to the metatarsal heads. For the knee extensor, the participant was seated with the hip and knee flexed to 90 degrees. The dynamometer was placed on the posterior aspect of the shank, proximal to the ankle joint. The child was able to stabilise themselves holding the edge of the assessment chair.

For the knee flexors, the participant was seated with the hips and knees flexed to 90 degrees. The dynamometer was placed on the posterior aspect of the shank, proximal to the ankle joint with the child stabilising themselves, as with the knee extensors. The child was asked to exert maximal force against the dynamometer in the direction of the desired movement for each test. A giraffe was used to show the child direction of movement required for each muscle group tested. This assisted in encouraging them to move the position of their leg/foot appropriately for the muscle testing. The lower limb was self-stabilised by the child in an attempt to isolate movements and minimise substitution movements. All movements were practiced with the child to obtain high quality contractions of two to five seconds for each muscle group. Three trials were performed, with the peak trial included in the analysis. All lower limb and foot measures were completed on the right side only as previous literature has reported a high correlation between left and right measures in non-pathological populations [7].

Figure 11 Lafayette hand-held dynamometer

3.5.4 Footwear sizing

Prior to the testing appointment, parents were directed to the sponsor's website (Appendix 4) to determine the correct footwear size for their child. Footwear size was re-measured by a researcher at the beginning of the testing session to ensure appropriate length and width fit. A different size of footwear was provided if there was a fit concern identified. Children were encouraged to walk around the room, with footwear habituation being less than five minutes. A longer habituation time was not possible due to the study protocol, and the limited data collection time-frame for each child. No formal measure of prior typical footwear use was recorded for each child. All children were observed wearing footwear prior to the testing session.

3.5.5 EMG

Five children were randomly selected from each age group (2, 3 and 4 year old groups) for collection of electromyography (EMG) data as a secondary measure using the Trigno™ (Delsys Inc, Massachusetts) system. Small sensors were placed on the key muscle groups, lateral gastrocnemius, biceps femoris and rectus femoris with a set protocol (Figure 12). A hypoallergenic tape was applied over the sensors to keep them in place. These sensors collected recruitment timing of each muscle group and muscle activity at the three muscle groups during walking and running in the three different footwear types.

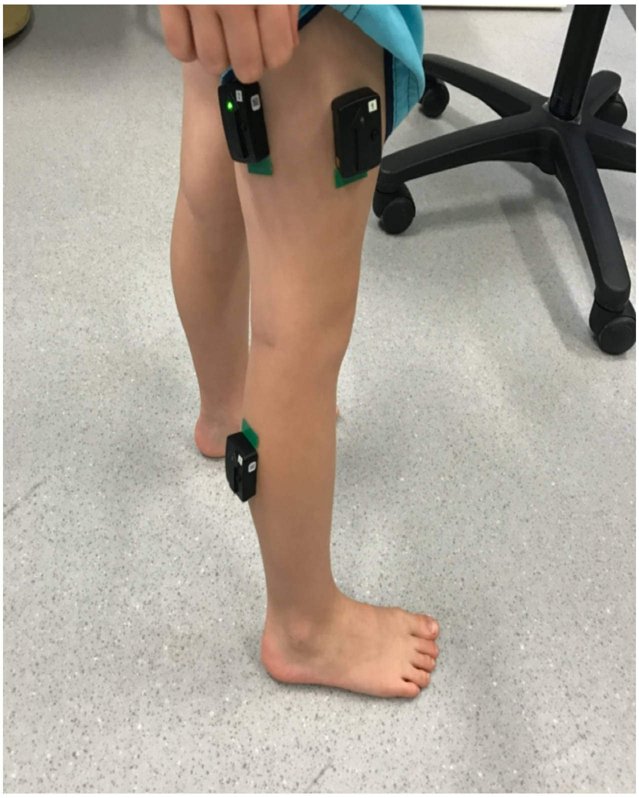


Figure 12 EMG Trigno sensor placement

3.6 Testing Procedure

On the day of testing, the following testing procedure sequentially occurred with each child:

1. Consent signed
2. The height, weight, and leg length measured
3. Weightbearing lunge test completed in leg straight and knee bent positions
4. Foot Posture Index–6 recorded
5. Manual muscle testing completed

6. If the child was in sequence of EMG data collection, skin was prepared and EMG sensors adhered to lateral gastrocnemius, hamstring and quadricep.
7. Condition order recorded
8. Shoe fit confirmed
9. Child introduced to the equipment
10. Child walked up and down the GAITRite mat with no recording
11. Allocated start condition recording commenced
12. Condition changed as per randomisation sequence
13. Repeat for additional 6 conditions according to sequence

Parents were emailed a visual schedule prior to the testing session. This visual schedule was developed with consultation of an experienced child psychologist. Parents were asked to show their child this visual schedule in preparation for the testing day (Figure 13). This provided each child with information to improve their familiarity of the space and testing requirements. This schedule was also used in person with participants to walk through the process during initiation to testing. As each participant completed a testing component, they were given a stamp to visualise task progression. A sticker was given as a reward at completion of all the testing requirements or when the child no longer wished to continue. All data were collected on the same day, within a single session for each participant.

Figure 13 Visual schedule of testing and reward chart

3.7 GAITRite Electronic Walkway

Walking and running trials were completed on a GAITRite Electronic Walkway (CIR Systems Inc. Havertown, PA, USA) 4.3 metre mat. The GAITRite was used to collect spatiotemporal measures of gait. This system has high reliability for these gait measurement in children [9]. Walking and running trials were completed at a self-selected speed, controlled across trials with a pace walker (researcher who matched the gait of the child and walked along side to minimize variation). The GAITRite set up had a 1.5 meter acceleration and deceleration run off at each end, limited to the size of the testing environment. Variable run off/on lengths have been reported in the literature, with one study reporting a 1 metre space at the start and end of the mat to accelerate or decelerate [10]. Participants repeated each walking or running trial three times in each shod condition. When a child deviated off the mat, the entire condition was repeated until three full trials were completed on the mat.

Children were assisted to stay on the mat by the use of visual markers on either side of the mat (Figure 14). The researchers alternated the side they walked or ran beside the participant dependent on where parents were standing in the room, which was consistent for each subject.

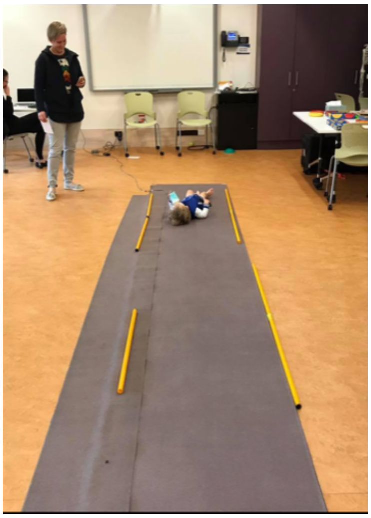


Figure 14 Visual markers

A toy post box was set up at the end of the mat to encourage children to walk or run along the mat. The majority of the participants carried a small letter, token or small item to post in the post box (Figure 15). The items were able to be carried in one hand, were small in size and weight, therefore thought to have minimal effect on the child's gait. Carried tokens were inconsistent between children, with some preferring not to or some alternating their carrying hands throughout testing.

Figure 15 Post box and items used within study for encouragement

3.8 Interventions: Footwear

There were three styles of footwear used within the study. The sandals had minor differences attributed to the sizing, however, all footwear had consistent ankle fixtures, sole pitch, heel counters and upper material. The different footwear included in the study were a sneaker, boot and sandal. Each sole was tested for sole hardness by the manufacturer prior to dispatch. This ensured consistency between the two sole hardness's being tested. The Shore of sole one was 48-53, and marketed as a 'soft sole' by the manufacturer, and medium/soft on the factory durometer shore hardness scale [11]. The Shore of two was 60-65 and marketed as a 'hard sole', considered as medium/hard on the factory durometer scale [11]. Each shoe sole was manufactured as a single unit of the same material. The increase in hardness of the sole was undertaken to increase the longitudinal stiffness of the footwear as a unit and a reduction in flexibility.

The sneaker (Figure 16) had features including a heel counter, minimal tred sole, and two Velcro straps which fastened the shoe to the foot. The sneaker weighed between 68g to 163g and had a 12mm to 17mm heel stack height and 11mm-12mm forefoot stack height dependent on the footwear size. There were no differences in appearance of the Shore A and Shore B sneaker.

Figure 16 Sneaker: Shore A (Left) and B (Right) Smaller size (front) Larger size (Back)

The sandal (Figure 17) had an ankle strap with a buckle and forefoot fixed strap. The sandal weighed between 72g to 140g, a heel stack height of 7mm to 12 mm, and a forefoot stack height of 7mm to 9.5mm dependent on the size of the footwear. There was a difference in the front of the sandal, with larger sizing having a forefoot buckle. The smaller sandals had a small covered heel counter with no structure and classified as fully flexible.

Figure 17 Sandal: Shore A (Left) and B (Right), Smaller size (front) Larger size (Back)

The boot (Figure 18) had the same sole construction and shape as the sandal, however, was fully enclosed and was adjustable for fit with a zip fastener on the inside aspect of the shoe. The single boot weighed between 75g to 160g, a heel stack height of 7mm to 12mm, and a forefoot stack height of 7mm to 9.5mm dependent on the size of the footwear.

Figure 18 Boot: Shore A (Left) and B (Right) Smaller size (front) Larger size (Back)

Pilot testing of the entire protocol was completed prior to the testing days to ensure adequate organisation on the day, and to trial with a child within the target age group to address challenges encountered before the study day.

3.9 References Chapter 3

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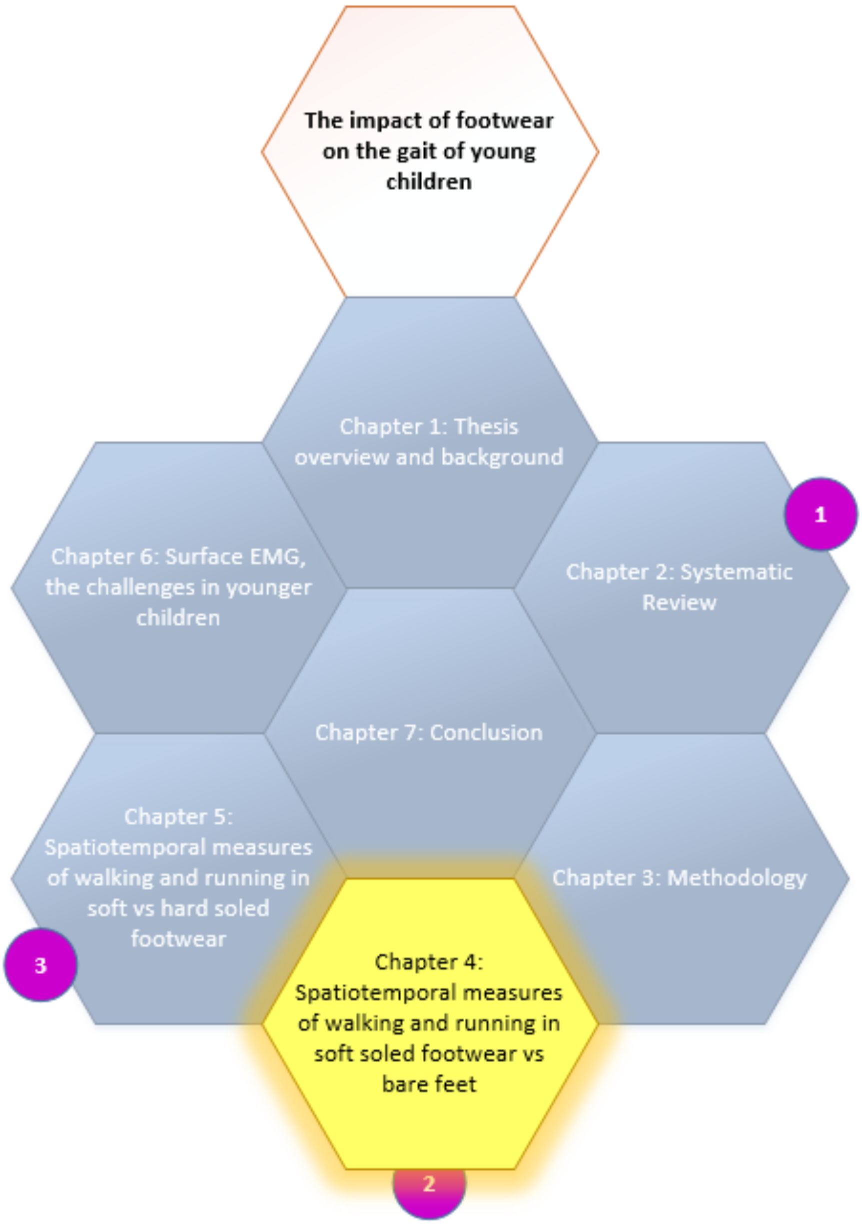
CHAPTER 4: Comparison of young children's spatiotemporal measures of walking and running in three common types of soft soled footwear compared to bare feet

4.1 Preamble



Chapter 2 outlined the limited exploration of the current evidence about footwear impact, in particular shoe features on younger children's gait. It explored the differences between shoe sole flexibility compared to barefoot in younger children, compared to children with more established gait patterns. The limited body of evidence has implications for footwear advice provided to parents, health professionals and footwear manufacturers. Parents are often advised that young children should wear soft soled footwear when they first beginning to walk independently. This advice is commonly based on the assumption that in comparison to hard soled footwear, soft-soled footwear is more similar to being barefoot in terms of spatiotemporal variables. However, this advice is not founded on evidence as shown in Chapter 2 of this thesis. In particular, the review highlighted the limited amount of research conducted on the impact of soft soled footwear on the gait of younger children. In addition, this research assists in determining if a soft sole is as close to barefoot as they are marketed to be. Therefore, to address this gap in the evidence, the study described in this chapter explored the differences in spatiotemporal measures of gait comparing soft-soled shoe types compared to barefoot in walking and running in young children.

4.1.1 Publication- Article 2

This article was published in Gait and Posture.

Cranage S, Perraton L, Bowles KA, Williams C. A comparison of young children's spatiotemporal measures of walking and running in three common types of footwear compared to bare feet. Gait Posture. 2020;81:218-24. https://doi.org/10.1016/j.gaitpost.2020.07.147

4.2 Declaration for Thesis Chapter 4

In Chapter 2, the nature and extent of my contribution to the work was the following:

Nature of contribution	Extent of contribution
Author	70%

The following authors contributed to the work:

Name	Nature of contribution	Extent of contribution
A/Prof Cylie Williams	Co-author	10%
Dr. Kelly-Ann Bowles	Co-author	10%
Dr. Luke Perraton	Co-author	10%

Author contribution: All authors contributed to the review concept and design. **SC**: Conceptualisation, Methodology, Validation, Formal analysis, Investigation, Writing- Original draft. **CW:** Conceptualisation, Methodology, Validation, Formal Analysis, Investigation, Writing- Review and editing, Supervision, Funding acquisition. **LP:** Methodology, Validation, Investigation, Writing- Review and editing, Supervision. **KAB:** Conceptualisation, Methodology, Formal Analysis, Investigation, Writing- Review and editing, Supervision

Declaration by co-authors:

The undersigned hereby certify that:

(1) The above declaration correctly reflects the nature and extent of the candidate's contribution to this work, and the nature of the contribution of each of the co-authors.

(2) They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;

(3) They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;

(4) There are no other authors of the publication according to these criteria;

(5) Potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit

Signature 1	A/Prof Cylie Williams	Date: 02/12/2020
		

Signature 2	Dr. Kelly-Ann Bowles	Date:25/01/2021
Signature 3	Dr. Luke Perraton	Date: 10/02/2021

4.3 Abstract

4.3.1 Background

Clinicians and footwear manufacturers often advise young children to wear soft-soled footwear when they are first learning to walk. There is limited evidence as to why this advice is given, and if soft-soled shoes are as close to barefoot as thought.

4.3.2 Research Question

What are the differences in spatiotemporal measures of gait during walking and running in three common types of children's footwear with a soft-soled compared to barefoot in young children?

4.3.3 Methods

The study used a quasi-experimental design, with the condition order randomised using a Latin square sequence. Forty-seven children were recruited (2 - 4 years). Participants walked or ran the length of a GAITrite mat in a randomized order for barefoot and soft-soled sneaker, boot and sandal conditions. Linear regression analyses were used to investigate the main effect of each soft-soled footwear compared to bare feet in the different gait parameters.

4.3.4 Results

For walking and running trials, cadence decreased whereas step time and stride length increased in all footwear types compared to the barefoot condition. While wearing sneakers and sandals increased the stance percentage for walking and running trials, compared to barefoot, this difference was only apparent during the running trial for the boots. Likewise, although double support time increased for both the boots and sneakers in walking and running, compared to barefoot, this difference was only observed in the sandals during walking.

4.3.5 Significance

This research found that various types of soft-soled footwear impacted gait compared to the barefoot condition, with some differences seen between walking and running trials.

These findings challenge the assumption that soft-soled footwear facilitate a similar gait to barefoot walking and running, although the clinical significance of these differences is unknown.

Keywords: Shoes, footwear, gait, barefoot, toddler, sole

4.4 Background

Footwear plays a number of different roles for children. The primary role is to provide foot protection from pain or injury associated with environmental elements and/or infection (1). Wearing footwear can allow children to interact with their outside environment. This assists them in advancing their skills and aides in their overall development (2). Most importantly, footwear helps children be active and play with their peers; therefore, it is important that footwear is fit for movement facilitation purposes (1). There have been a number of studies investigating different types of footwear and the gait impact of footwear in children. These studies have limited exploration to the spatiotemporal, kinematics and kinetics, plantar loading and muscle activity of either very young children during walking acquisition while barefoot, or children over the ages of six (3-8). Spatiotemporal variables in older children have shown to change with increasing age, and wearing footwear increases velocity, step and stride length (8), and decreases their cadence and swing percentage (6) compared to barefoot. It is unknown if these differences attributed to footwear occur in younger children who commonly also display different gait paramaters due to their immaturity (9).

Young children's feet change over time with a number of structural adaptations that align with developmental stages such as growth rate, plasticity of the foot and gross motor development (10, 11). Therefore, there is an assumption that footwear should have minimal impact on developing foot function or gross motor development and that this should be a fundamental factor in choosing footwear for a young child (12).

Children commonly wear footwear outside, so understanding how footwear impacts movement such as walking or running is important. This knowledge may assist health professions to provide accurate information to parents in order for them to make choices about their children's footwear. This knowledge may also have a role in moderating how footwear risks and benefits are promoted to parents. This is particularly important as children learn and improve gross motor skills at different ages, in line with substantial foot structural changes throughout childhood (13, 14). Therefore, footwear choices are important due to the potential influence on foot development and gross motor function, in particular implications on longer term foot health (15, 16). It is a historical belief that the barefoot environment promotes optimum foot development (16) and by default, better walking, running or gross motor performance (17). Research in children over the age of six has also shown an association that regular physical activity without footwear may be beneficial for the development of gross motor skills, including jumping and balance (18). As a result, many clinicians and footwear manufacturers often advise children to wear soft-soled footwear when they are first learning to walk. This advice is based on the premise that the soft-soled footwear is as close to barefoot as possible. However, there is limited evidence in younger children to support or confirm that sole softness (or hardness) plays a role in movement patterns. This can often lead to conflicting footwear advice given to parents of younger children (14).

This research aimed to investigate the differences in spatiotemporal measures of gait between walking and running in a selection of soft-soled shoes compared to barefoot in young children.

4.5 Methods

4.5.1 Study design

A quasi-experimental design, with condition order (barefoot/shod, walking/running) nested within a larger trial (ACTRN12617000999336) (Appendix 1). The Human Research Ethics Committee of Monash University, Victoria Australia approved this research (HREC/17/8549) (Appendix 2). Parents of included children provided written consent, and all children assented to participate.

4.5.2 Participants and setting

Participants were aged between two and four years, with no medical conditions known to impact on gait (Parent report). Participants were recruited in May 2017 during winter and was completed within one week through social media advertisements (Facebook, Twitter), and university newsletters. Data were collected at Monash University gait laboratory.

4.5.3 Measures and outcomes

Anthropometric data was collected. Measures included age, gender, footwear size, height, weight and body mass index (BMI). Additional lower limb descriptors incorporated measures of foot and ankle joint position and strength including weight bearing ankle joint range of motion (19, 20) and Foot Posture Index -6 (21). Isometric muscle strength (22) of the knee extensors/flexors and ankle dorsiflexors/plantarflexors were also tested using a hand held dynamometer. Lower limb and foot measures were all performed on the right leg only due to a high correlation between the left and right limb measures in non-pathological populations (23).

All measures were taken by a single clinician with experience in assessment of children's foot and lower limb and routinely uses these measures in clinical settings. Walking and running trials were completed on a GAITRite Electronic Walkway (CIR Systems Inc. Havertown, PA, USA) 4.3 metre mat. This system has high reliability for gait walking measurement of children (24). The GAITRite was used to collect spatiotemporal measures of gait (Table 6). The primary outcome was step length, a commonly observed variable impacted by footwear compared to barefoot walking (3). Additional spatiotemporal measures were also included if they had previous reported footwear impact (3, 25).

Table 6 Spatiotemporal measures definition

Spatiotemporal measures	Definition
Stride length (cm)	Measurement from the heel points of two consecutive steps of the same foot
Step length (cm)	Measurement of the heel points of two consecutive steps from one foot to the other
Toe in/out (degrees)	The angle between the middle of the steps and the middle of the foot
Step time (sec)	Time between the first contact of one foot to the first contact of the other foot
Stride time (sec)	Time between the first contact of one foot to the first contact of that foot again
Velocity (cm/sec)	The distance walked divided by the speed
Swing percentage (%)	Percentage of the gait cycle when the foot is not in contact with the ground
Stance percentage (%)	Percentage of the gait cycle with feet in contact with the ground
Double support time (sec)	Time during walking when both feet are on the ground
Cadence (steps/min)	Number of steps taken per minute

The number of trips or stumbles were also recorded during the testing. A stumble was defined as the toe contacting the ground during swing phase and initiating a trip. A member of the research team who was walking alongside the participant visually observed the tripping and this was manually recorded.

Interventions

The intervention of interest was a sneaker, boot and sandal style of footwear (Figure 19-21). Prior to factory dispatch, each sole was tested for uniform sole hardness by the manufacturer and was remanufactured if not within the acceptable limit. This ensured a consistent Shore A hardness of 48-53 and marketed as a “soft sole” by the manufacturer and medium/soft on the durometer shore hardness scale. The sneaker footwear (Figure 19) features included a heel counter, flat sole and two velcro straps fastening it to the foot. The sandals (Figure 20) and boots (Figure 21) had the same sole shape and material; however, the boot had a side zip and heel counter, and the sandal had an ankle strap with a buckle and forefoot fixed strap. There were minimal variations between the soles and between sizes for each of the footwear. Each shoe sole was manufactured as a single unit of the same material. There were differences between sizes and the sizes 20 EU and 30 EU were used to describe these differences. The single boot weighed between 75g to 160g, sandal weighed between 72g to 140g and sneaker weighed between 68g to 163g. Both the boot and sandal had a 7mm to 12mm heel stack height and 7mm to 9.5mm forefoot stack height due to the same sole construction and shape. The sneaker had a 12mm to 17mm heel stack height and 11mm-12mm forefoot stack height.

Figure 19 Footwear used within study- Sneakers Shore 48-53

Figure 20 Footwear used within study- Sandals Shore 48-53

Figure 21 Footwear used within study- Boots Shore 48-53

Testing conditions included:

- Condition 1 – Barefoot walking at self-selected pace
- Condition 2 – Barefoot running at self-selected pace
- Condition 3 – Self-selected paced walking in sneaker style footwear
- Condition 4 – Self-selected paced running in sneaker style footwear
- Condition 5 – Self-selected paced walking in boot style footwear
- Condition 6 – Self-selected paced running in boot style footwear
- Condition 7 – Self-selected paced walking in sandal style footwear
- Condition 8 – Self-selected paced running in sandal style footwear

4.5.4 Procedures

Prior to the testing appointment, parents were directed to the website of the footwear manufacturer to follow the website's instructions for measuring their child's feet and determining shoe size prior to testing to ensure research team had access to size on testing day. Footwear sizing was re-assessed on the day of testing and the size was modified if required. Children were encouraged to walk around the room therefore shoe habituation was less than five minutes. A larger habituation timeframe was not possible due to the study protocol and data collection time frame. All children commonly were barefoot or wore shoes depending on the weather or activity, no formal measure of shoe wear percentage, times/day or week were recorded.

Parents were provided with a visual schedule of testing processes to share with their child in preparation to provide familiarity with the space and research team. On the day, participants walked through the process with their visual reward chart. As each participant completed each testing component, they were given a stamp for visualize task progression.

The GAITRite set up had a 1.5 metre acceleration and deceleration run off at each end. As part of the orientation, participants practiced a walk or run pace and a researcher walked along side to match and attempt to standardise participants speed between trials. The researchers who were gaiting the speed did not always walk or run on the same side, this was random based on room arrangement for individual participants.

Once familiar, participants walked or ran the length of the GAITRite mat in a randomized order for the bare foot and soft-soled sneaker, boot and sandal conditions. Randomisation was completed using a Latin square sequence to account for order fatigue. Participants repeated each walking or running trial three times.

Participants were supported to keep on the GAITRite mat through a “posting” technique. A post box was set up at the end of the mat and participants carried a small letter or token to post. The small items chosen were determined by the research team to have minimal impact on their gait throughout testing due to minimal size, weight and able to be carried in one hand. This was inconsistent between the children, as some did not carry any tokens and there was variable hand preference to those that did. Where required, visual markers were placed on the sides of the mat to ensure gait centering for data collection.

4.5.5 Data Analysis

Data were analysed in Stata 13 (26). All foot prints were visualized within the GAITRite software, and any partial foot prints were removed prior to analysis. A trial was counted if the child stayed on the mat, for majority of the length of the mat, and completed three lengths of the mat. Complete case analysis was used with cleaned data.

Linear regression analyses clustered by participant, were used to investigate the main effect of soft-soled sneakers, boot and sandal compared to bare foot for the different gait parameters and speeds. Data were clustered within individual participants and robust variance estimates were used to account for the within-subject nature of the study design.

The regression coefficient and 95% confidence intervals were calculated. This data analysis plan was to reduce variability by comparing the changes observed between each individual child. Effect sizes (ES) were calculated using the mean difference between the shod and barefoot conditions and dividing this by the pooled standard deviation of the first condition (27). Effect sizes were considered as small (<0.6), medium (0.61-1-19), or large ($\geq$1.2) (28). Statistically significant differences were considered where $p<0.05$. A sample size of 30 children were required to achieve 80% power with a minimum effect size of 0.530 as a result of the difference in shod walking conditions of step length using an alpha criterion of 0.05 (3).

4.6 Results

Participants had similar anthropometric data for ankle range of motion, FPI-6 and strength measures, as other published data of typically developing children (Table 7)(29).

Table 7 Anthropometric data

	All children Mean (SD) or N (%)	2 year olds Mean (SD) or N (%)	3 year olds Mean (SD) or N (%)	4 year olds Mean (SD) or N (%)
Participant numbers	47	15	17	15
Completed trials		9 (60%)	14 (82%)	14 (93%)
Partial trials		6 (40%)	3 (18%)	1 (7%)
Gender (Female)	25 (53%)	7 (47%)	10 (59%)	8 (53%)
Height (cm)	99.51 (6.84)	92.70 (3.25)	99.42 (4.88)	106.44 (3.83)
Weight (kg)	16.58 (2.28)	14.69 (1.90)	16.46 (1.67)	18.6 (1.41)
BMI Kg/m^2	16.66 (1.33)	17.05 (1.84)	16.61 (1.67)	16.35 (0.83)
Ankle ROM – Knee extended (degrees)	33.12 (3.89)	32.73 (3.17)	32.65 (3.93)	34.00 (4.48)
Ankle ROM – Knee bent (degrees)	41.71 (4.83)	42.82 (5.37)	38.53 (4.18)	44.34 (2.81)
FPI-6 (Right only)	4.21 (1.36)	4.80 (0.94)	3.88 (1.58)	4.00 (1.46)
Hamstring strength (Newtons)	45.65 (13.17)	34.43 (11.02)	41.43(7.63)	55.76(10.18)
Quadriceps Strength (Newtons)	67.16 (22.20)	46.17 (17.26)	68.01 (19.45)	83.08(14.72)
Gastrocnemius/Soleus Strength (Newtons)	71.20 (24.52)	51.26(21.54)	71.65 (23.81)	82.17 (12.67)

The cohort's spatiotemporal gait variables and effect sizes comparing walking in barefoot to the shod conditions are displayed in Table 8 with gait data presented by age in supplementary data table. All footwear types decreased cadence compared to barefoot walking. While there was no difference observed across any of the footwear types in velocity between shod and barefoot walking, step time and stride length were observed to increase in all footwear types compared to the barefoot condition. While wearing the sneakers and sandals, there was an increase in stance percentage and a decrease in swing percentage compared to barefoot, however there was no differences seen in these variables while wearing the boots. Double support time increased across all footwear conditions when compared to barefoot walking, and there were variable differences in the toe in/out angle across the same comparison. Sneakers had a medium effect on most gait variables excluding velocity, and toe in/out angle resulted in a small effect. Boots had a medium effect on less variables than sneakers, resulting in small effects on cadence, step time (left only), swing and stance percentage and toe in/out angle. Similar to sneakers, the sandals had a medium effect on most gait variables excluding velocity, step time (left), toe in/out and the number of steps. All effects were compared to the barefoot condition.

Table 8 Mean, standard deviation (SD), regression coefficient, 95% confidence interval (CI), statistical significance and effect size for spatiotemporal variables for barefoot versus soft sneakers, boots and sandals in walking

	Barefoot ***Mean (SD)***	**Sneakers** ***Mean (SD)***	**Barefoot versus sneakers** ***Coef [95% CI], p value***	**Effect size (Cohen's *d*)**
Velocity (cm/sec)	99.91(16.64)	102.68(19.80)	2.77[-1.62, 7.17], 0.21	0.15
Cadence (steps/min)	155.68(17.42)	141.41(14.16)	-14.28[-18.61, -9.94], <0.001	0.90
Left step time (sec)	0.39(0.05)	0.43(0.05)	0.04 [0.02, 0.05], <0.001	0.80
Right step time (sec)	0.39(0.04)	0.43(0.05)	0.04 [0.03, 0.05], <0.001	0.88
Left stride length (cm)	77.46(11.35)	87.12(13.07)	9.66 [7.08, 12.25], <0.001	0.79
Right stride length (cm)	77.43(11.42)	87.05(13.15)	9.63 [6.96, 12.29], <0.001	0.78
Left swing percentage (%)	41.23(1.54)	39.9(1.47)	-1.33 [-1.74, -0.92], <0.001	0.88
Right swing percentage (%)	41.08(1.92)	39.98(1.65)	-1.10 [-1.66, -0.53], <0.001	0.61
Left stance percentage (%)	58.78(1.54)	60.10(1.46)	1.32 [0.90, 1.73], <0.001	0.88
Right stance percentage (%)	58.90(1.92)	60.02(1.65)	1.12 [0.56, 1.67], <0.001	0.63
Left double support time (sec)	0.14(0.03)	0.17(0.04)	0.04 [0.03, 0.04], <0.001	0.85
Right double support time (sec)	0.14(0.03)	0.17(0.04)	0.04 [0.03, 0.05], <0.001	0.85
Left toe in/out (degree)	-1.39(5.16)	-0.72(5.11)	0.67 [-0.58, 1.92], 0.28	0.13
Right toe in/out (degree)	-1.42(5.77)	0.61(5.17)	2.03 [1.01, 3.06], <0.001	0.37
Steps (count)	28 (6)	24 (4)	-3.91 [-5.78, -2.03], <0.001	0.70
		Boots	**Barefoot versus boots**	
Velocity (cm/sec)		107.53(37.28)	7.62[-2.57-17.82], 0.14	0.26
Cadence (steps/min)		144.95(20.61)	-10.73[-17.76, -3.71], <0.001	0.56
Left step time (sec)		0.42(0.05)	0.03 [0.01, 0.05], <0.001	0.60
Right step time (sec)		0.42(0.05)	0.03 [0.01, 0.05], <0.001	0.66
Left stride length (cm)		88.01(15.78)	10.55 [7.40, 13.69], <0.001	0.77
Right stride length (cm)		87.80(15.82)	10.38 [7.30, 13.46], <0.001	0.75
Left swing percentage (%)		40.6(4.03)	-0.63 [-1.87, 0.62], 0.32	0.21
Right swing percentage (%)		40.42(4.18)	-0.66 [-1.80, 0.48], 0.25	0.20
Left stance percentage (%)		59.4(4.03)	0.62 [-0.63, 1.86], 0.32	0.20
Right stance percentage (%)		59.58(4.18)	0.69 [-0.45, 1.82], 0.23	0.21
Left double support time (sec)		0.17(0.04)	0.03 [0.02, 0.04], <0.001	0.85
Right double support time (sec)		0.17(0.04)	0.03 [0.02, 0.04], <0.001	0.85
Left toe in/out (degree)		0.27(4.59)	1.66 [0.62, 2.69], <0.001	0.34
Right toe in/out (degree)		1.01(4.91)	2.43 [1.46, 3.40], <0.001	0.45
Steps (count)		24 (4)	-4.07 [-5.82, -2.32], <0.001	0.69
		Sandals	**Barefoot versus sandals**	
Velocity (cm/sec)		101.50(18.74)	1.59[-2.64, 5.82] 0.45	0.09
Cadence (steps/min)		143.63(14.61)	-12.05[-17.08, -7.01], <0.001	0.75
Left step time (sec)		0.42(0.05)	0.03 [0.02, 0.05], <0.001	0.60
Right step time (sec)		0.42(0.05)	0.03 [0.02, 0.05], <0.001	0.66
Left stride length (cm)		84.98(13.02)	7.52 [5.67, 9.37], <0.001	0.62

Right stride length (cm)	85.01(12.80)	7.59 [5.75, 9.43], <0.001	0.62
Left swing percentage (%)	39.88(2.08)	-1.35 [-1.94, -0.75], <0.001	0.74
Right swing percentage (%)	39.73(2.15)	-1.25 [-1.89, -0.81], <0.001	0.66
Left stance percentage (%)	60.11(2.09)	1.33 [0.74, 1.93], <0.001	0.72
Right stance percentage (%)	60.28(2.13)	1.38 [0.85, 1.92], <0.001	0.68
Left double support time (sec)	0.17(0.04)	0.04 [0.02, 0.05], <0.001	0.85
Right double support time (sec)	0.17(0.04)	0.04 [0.03, 0.05], <0.001	0.85
Left toe in/out (degree)	1.14(5.21)	2.54 [1.37, 3.71], <0.001	0.49
Right toe in/out (degree)	0.71(5.76)	2.14 [0.79, 3.49], <0.001	0.37
Steps (count)	25 (5)	-2.90 [-4.88, -0.92], <0.001	0.51

The spatiotemporal measures of gait comparing running in barefoot to the shod conditions are displayed in Table 9. Cadence decreased in the cohort for all footwear conditions compared to barefoot, similar to walking. There was no difference in velocity between shod and barefoot running. Step time and stride length increased across all of the footwear types compared to barefoot running however, there were no differences observed in the swing or stance percentage in all footwear with the same comparisons. Double support time increased in the sneakers and boots compared to barefoot running, however there was no observed difference in the sandals. Toe in/out measures were variable between the footwear and barefoot conditions with no differences observed in the boots, however differences in the sneakers and sandals.

All footwear had a medium effect on cadence, sneakers and boots also had a medium effect on step time (left foot only), and all other footwear effects were small.

Table 9 Mean, standard deviation (SD), regression coefficient, 95% confidence interval (CI), statistical significance and effect size for spatiotemporal variables for barefoot versus soft sneakers, boots and sandals in running

	Barefoot *Mean (SD)*	**Sneakers** *Mean (SD)*	**Barefoot versus sneakers** *Coef [95% CI], p value*	**Effect size** *(Cohen's d)*
Velocity (cm/sec)	270.31(62.96)	275.83(50.72)	5.52[-5.42, 16.46], 0.32	0.10
Cadence (steps/min)	252.76(14.05)	239.38(12.43)	-13.38 [-17.92, -8.84], <0.001	1.01
Left step time (sec)	0.24(0.02)	0.25(0.01)	0.01 [0.01, 0.02], <0.001	0.63
Right step time (sec)	0.24(0.02)	0.25(0.02)	0.01 [0.01, 0.02], <0.001	0.50
Left stride length (cm)	128.49(29.68)	138.42(25.39)	9.94 [4.82, 15.06], <0.001	0.36
Right stride length (cm)	129.38(30.30)	139.18(25.52)	9.81 [4.78, 14.83], <0.001	0.39
Left swing percentage (%)	61.18(4.41)	62.16(3.00)	0.98 [-.0.12, 2.07], 0.08	0.26
Right swing percentage (%)	61.56(4.64)	62.19(3.45)	0.63 [-0.42, 1.68], 0.23	0.15
Left stance percentage (%)	38.83(4.40)	37.86(2.98)	-0.96 [-2.04, 0.17], 0.08	0.26
Right stance percentage (%)	38.48(4.62)	37.82(3.43)	-0.67 [-1.71, 0.38], 0.21	0.16
Left double support time (sec)	0.12(0.04)	0.13(0.04)	0.01 [0.00-0.02], 0.016	0.25
Right double support time (sec)	0.11(0.04)	0.12(0.03)	0.01 [0.00, 0.02], <0.001	0.28
Left toe in/out (degrees)	1.48(9.97)	5.54(5.29)	4.07 [1.78, 6.36], <0.001	0.51
Right toe in/out (degrees)	3.18(9.11)	6.59(6.42)	3.42 [1.17, 5.66], 0.004	0.43
Steps (count)	17 (6)	15 (4)	-2.38 [-3.78, -0.98], 0.001	0.37
		Boots	**Barefoot versus boots**	
Velocity (cm/sec)		275.03(56.70)	-4.72[-12.62, 3.18], 0.24	0.08
Cadence (steps/min)		239.66(12.41)	-13.10 [9.30, 16.89], <0.001	0.99
Left step time (sec)		0.25(0.01)	0.01 [-0.02, -0.01], <0.001	0.63
Right step time (sec)		0.25(0.02)	0.01 [-0.02, -0.01], <0.001	0.50
Left stride length (cm)		138.35(28.61)	9.86 [-13.26, -6.46], <0.001	0.34
Right stride length (cm)		138.32(28.32)	8.95 [-12.49, -5.41], <0.001	0.34
Left swing percentage (%)		61.8(3.64)	0.62 [-1.53, 0.29], 0.18	0.15
Right swing percentage (%)		62.08(3.98)	0.52 [-1.36, 0.31], 0.21	0.12
Left stance percentage (%)		38.22(3.62)	-0.61 [-0.30, 1.51], 0.18	0.15
Right stance percentage (%)		37.93(3.98)	-0.55 [-0.29, 1.39], 0.19	0.13
Left double support time (sec)		0.12(0.04)	-0.01 [-0.02, -0.00], 0.03	0.00
Right double support time (sec)		0.12(0.04)	-0.01 [-0.02, -0.00], <0.001	0.25
Left toe in/out (degrees)		4.51(6.92)	-3.03 [-5.23, -0.84], <0.001	0.35
Right toe in/out (degrees)		5.20(7.57)	-2.02 [-4.27, 0.22], 0.08	0.24
Steps (count)		15 (5)	-2.2 [-3.48, -1.05], <0.001	0.36
		Sandals	**Barefoot versus sandals**	
Velocity (cm/sec)		266.28(52.86)	4.02[-6.70, 14.75], 0.45	0.07
Cadence (steps/min)		239.01(16.16)	-13.74 [8.35, 19.14], <0.001	0.91
Left step time (sec)		0.25(0.02)	0.02 [-0.02, -0.01], <0.001	0.50
Right step time (sec)		0.25(0.02)	0.01 [-0.02, -0.01], <0.001	0.50
Left stride length (cm)		134.72(28.24)	6.23 [-10.75, -1.70], <0.001	0.22

Right stride length (cm)	134.37(27.87)	5.9 [-9.70, -0.30], 0.04	0.17
Left swing percentage (%)	60.83(3.93)	0.36 [-0.66, 1.37], 0.05	0.08
Right swing percentage (%)	60.9(4.11)	0.66 [-0.35, 1.66], 0.20	0.15
Left stance percentage (%)	39.17(3.91)	-0.35 [-1.35, 0.66], 0.49	0.08
Right stance percentage (%)	39.08(4.11)	-0.59 [-1.59, 0.40], 0.24	0.14
Left double support time (sec)	0.11(0.04)	0.00 [-0.01, 0.01], 0.73	0.25
Right double support time (sec)	0.11(0.04)	-0.00 [-0.01, 0.01], 0.88	0.00
Left toe in/out (degrees)	5.53(7.30)	-4.05 [-6.48, -1.62], <0.001	0.46
Right toe in/out (degrees)	6.68(6.77)	-3.50 [-5.66, -1.34], <0.001	0.44
Steps (count)	15 (4)	-2.03 [-3.39, -0.66], 0.004	0.38

There were no stumbles (0%) during any of the trials during walking or running barefoot (46 trials) or during running in the soft soled sneakers (42 trials) or boots (43 trials). There were two stumbles (7%) during walking in the soft soled sneakers (43 trials), two stumbles (4%) in the soft sandals (47 trials) and two stumbles (4%) in the boots (43 trials). There was one stumble (2%) during running in the soft sandals (46 trials).

4.7 Discussion

This is the first study undertaken in children of this age group with footwear that is commercially available (25). Wearing footwear resulted in gait changes in walking and running compared to walking or running barefoot, however it is unknown if these changes are clinically significant. The footwear had variable features that may have resulted in some of the similarities and differences observed between walking and running barefoot compared to wearing footwear. These features may be related to the similarity in soles between the boot and the sandal. Likewise, the adjustable fit of the sneaker and sandal may have been a reason for other similarities. There were particular findings that have not been observed in shod adults and older children and may be a result of the footwear or the different typical gait patterns naturally observed in young children.

Wearing different footwear however also resulted in similar gait changes observed in each shoe compared to barefoot walking and running. Young children also exhibited a number of differences in their walking and running in each of the different footwear styles compared to older children or adults when wearing footwear. In particular, there were no differences in children's velocity regardless of whether they were walking or running the sneakers, boots or sandals. Older children (aged between 5-11 years) have demonstrated increasing their velocity while wearing footwear compared to barefoot conditions (3, 7). Yet the velocity increase was not observed in this younger age group, which may be due to less confidence and adaptability in unfamiliar surroundings, or less conditioning to wearing footwear.

Therefore, they may not exhibit the same gait confidence in the form of velocity in comparison to older children. It is possible these differences may also be attributed to a less mature gait pattern, therefore being less able to adapt gait velocity regardless of the footwear condition. Studies have found age normalized velocity gradually increases from the age of one to four years and stabilizes between five to ten years (9), which might explain some of the lack of differences seen in velocity in the younger children.

Cadence consistently decreased across all footwear styles compared to barefoot. Cadence of younger children shows evidence of maturation of the central nervous system and growth until 4 years of age. After the age of 4 years, the changes in cadence are said to be attributed to changes in limb length with the cadence of a younger child being higher than an older child (9). This results from having a shorter leg length, therefore requiring an increased number of steps to cover any distance. This is consistent with what is known in older children (3, 6-8).

Another similarity with older children was the younger children increased their stride length in walking and running in all footwear conditions compared to barefoot. This could be a result of the shoe sole elongating the foot, therefore increasing their stride length, in addition to taking fewer steps per minute. By adding a medium/soft sole and creating a resistance bend in the shoe creates an assumption that a more solid structure may have facilitated some foot rigidity. This may have increased stride length, potentially related to the shoe making the foot a rigid lever, therefore increasing the push off force generated at toe off, however further research is required to understand this potential mechanism.

Another potential influencing factor in stride length may have been the sole height of the footwear. By adding footwear with a sole height of 7-17mm to a young child, this increases the leg length by this amount, therefore we would expect a minor increase in their stride length. The increase in stride length in both walking and running while wearing footwear could also potentially reflect the slightly longer leg length. This increase in leg length in relationship to the shoe sole height, has previously been described as a potential impact in studies in older children (3, 30). This element of protection that footwear can provide may result in the child having confidence to stride out further (1, 30). Noting that velocity did not change in conditions, it is logical as stride length increases the children took fewer steps per minute.

The increase in stance percentage and a decrease in swing percentage during walking in soft-soled sneakers and sandals compared to barefoot, was not seen in the boot condition. These differences were not observed during running, which may be a result of fixtures and footwear fit. Therefore, footwear with fixtures may reduce gait differences between shod and barefoot, especially in children who have less experience wearing shoes. Shoes could also act as a sensory filter, therefore reducing the proprioceptive input again leading to gait changes to increase stability (30).

The variable toe in-out angle during gait could be attributed to the age of the children. While rotational profiles were not measured, there is known variability within the foot progression angle in children' gait due to anatomical variations (31). Young children often have an internal foot progression angle during gait, and this is a typical variant which reduces with growth (31). This often results in variation of foot placement during walking (31).

While footwear companies attempt to create a shoe that mimics barefoot as much as possible with a softer sole, this study has shown that different types of footwear change gait variables in walking and running. However, given the medium effect of all of these changes, it is difficult to extrapolate these findings of gait impact to clinical recommendations for any footwear benefits or harm.

There are a number of limitations within this research. The artificial environment of the testing may impact the results of the study. While the GAITRite has a high reliability for gait walking measurement of children, the researchers are unaware of any reliability studies for children's running. Members of the research team who conceptualized this research have extensive paediatric experience, however the laboratory environment was new to the participants. Therefore, it is important to note these results may be different in real life, particularly as children walk or play on different surfaces and playground equipment. It was not feasible to complete a footwear habituation period because of the study design. Our study was limited to spatiotemporal measurements, and there are other important variables that need to be taken into consideration such as comfort, muscle activation and force. Additionally, there are no published definitions of footwear features and classifications for young children's footwear. This means other footwear research carried out with young children, using commercially available footwear, may not be comparable if the footwear is described differently or the features substantially vary.

4.8 Conclusion

It is important that footwear messages are based on the best available evidence, and that messages are consistent for parents when buying footwear for their children. It is also important to offer health messages based on evidence to inform clinician's recommendations and decisions around appropriate footwear for young children where there is thought to be a therapeutic impact. As a result of this study, we propose that clinicians can cautiously inform parents of the minimal impact of the soft-soled footwear used in this study on walking and running, however it is not the same as a child walking in bare feet. Future research should investigate how different footwear features, such as shoe sole density, impacts the gait of young children. Researchers should also consider standardising descriptions for young children's footwear and how their features are described.

4.9 Supplementary File A

Gait parameters of 2 year old children (n=15) for walking or running in four shod/unshod conditions

	Barefoot Walk Mean (SD)	Barefoot Run Mean (SD	Sandal Walk Mean (SD)	Sandal Run Mean (SD)	Sneaker Walk Mean (SD)	Sneaker Run Mean (SD)	Boot Walk Mean (SD)	Boot Run Mean (SD)
Velocity (cm/s)	89.15(13.45)	197.39(39.14)	89.26(22.08)	203.58(30.20)	85.35(16.20)	215.39(31.39)	90.66(16.31)	208.93(33.79)
Cadence	156.45(16.90)	249.14(20.09)	143.54(20.30)	242.02(18.60)	137.59(17.96)	239.66(11.02)	141.3(11.02)	240.42(13.77)
Left step time (s)	0.39(0.04)	0.24(0.02)	0.43(0.06)	0.25(0.02)	0.44(0.06)	0.25(0.01)	0.43(0.04)	0.25(0.02)
Right step time (s)	0.39(0.42)	0.25(0.03)	0.42(0.07)	0.25(0.03)	0.44(0.06)	0.25(0.02)	0.43(0.04)	0.25(0.02)
Left stride length (cm)	68.95(9.50)	95.31(17.63)	74.11(12.33)	101.82(14.68)	74.26(6.62)	108.23(16.53)	77.20(10.32)	105.27(17.98)
Right stride length (cm)	68.77(9.67)	95.65(18.69)	74.27(12.06)	101.45(14.41)	74.28(6.89)	109.55(18.08)	76.90(10.07)	104.84(17.54)
Left swing percentage (%)	40.31(1.71)	56.58(5.08)	39.29(2.91)	57.04(3.47)	39.06(1.54)	59.53(3.84)	39.22(2.47)	57.81(3.41)
Right swing percentage (%)	40.43(2.36)	57.28(5.88)	38.82(2.70)	56.95(4.33)	39.35(1.28)	59.82(5.11)	39.59(2.70)	58.42(4.59)
Left stance percentage (%)	59.71(1.69)	43.42(5.05)	60.71(2.92)	42.95(3.43)	60.94(1.53)	40.53(3.76)	60.79(2.47)	42.19(3.33)
Right stance percentage (%)	59.56(2.34)	42.74(5.88)	61.18(2.70)	43.03(4.36)	60.65(1.29)	40.22(5.05)	60.42(2.69)	41.6(4.58)
Left double support time	0.15(0.04)	0.08(0.04)	0.19(0.06)	0.07(0.03)	0.19(0.04)	0.10(0.05)	0.18(0.05)	0.08(0.04)
Right double support time	0.25(0.04)	0.08(0.04)	0.19(0.06)	0.07(0.03)	0.20(0.04)	0.10(0.04)	0.18(0.05)	0.09(0.04)
Left toe in/out	0.28(5.00)	2.47(4.11)	1.99(4.88)	3.53(4.18)	-0.43(4.67)	4.69(4.60)	0.54(4.14)	2.91(4.36)
Right toe in/out	0.08(5.00)	3.55(6.66)	2.44(5.78)	6.42(6.07)	1.72(4.05)	5.28(4.86)	2.06(5.22)	4.89(6.06)

Gait parameters of 3 year old children (n=17) for walking or running in four shod/unshod conditions.

	Barefoot Walk Mean (SD)	Barefoot Run Mean (SD	Sandal Walk Mean (SD)	Sandal Run Mean (SD)	Sneaker Walk Mean (SD)	Sneaker Run Mean (SD)	Boot Walk Mean (SD)	Boot Run Mean (SD)
Velocity (cm/s)	100(18.11)	274.15(40.52)	100.47(12.96)	270.27(39.04)	102.58(14.97)	275.39(36.55)	100.29(17.10)	276.83(36.89)
Cadence	160.11(20.46)	256.53(11.24)	146.14(11.73)	238.98(17.51)	145.48(11.29)	239.51(15.70)	143.9(14.06)	239.15(13.92)
Left step time (s)	0.38(0.06)	0.23(0.01)	0.41(0.04)	0.25(0.02)	0.41(0.03)	0.26(0.02)	0.42(0.04)	0.25(0.01)
Right step time (s)	0.38(0.05)	0.23(0.02)	0.42(0.03)	0.25(0.02)	0.41(0.03)	0.25(0.02)	0.42(0.04)	0.25(0.02)
Left stride length (cm)	75.27(7.38)	128.02(19.43)	82.86(6.92)	135.72(19.73)	84.71(8.88)	138.55(19.16)	83.50(8.85)	139.05(18.16)
Right stride length (cm)	75.17(7.19)	129.30(19.84)	82.81(6.71)	136.84(20.33)	84.47(8.53)	138.47(18.78)	83.47(8.63)	140.13(18.86)
Left swing percentage (%)	41.65(1.48)	62.6(2.72)	39.6(1.94)	61.72(3.38)	39.83(1.36)	63.2(2.57)	40.15(1.57)	63.20(2.81)
Right swing percentage (%)	41.39(2.09)	63.06(2.79)	40.39(2.03)	62.35(2.85)	39.63(1.52)	62.99(2.59)	39.81(1.82)	63.18(3.13)
Left stance percentage (%)	58.34(1.49)	37.41(2.72)	60.4(1.94)	38.27(3.36)	60.18(1.33)	36.79(2.55)	59.86(1.58)	36.86(2.79)
Right stance percentage (%)	58.61(2.10)	37.04(2.74)	59.64(2.0)	37.64(2.83)	60.36(1.52)	37.02(2.57)	60.2(1.82)	36.83(3.16)
Left double support time	0.13(0.04)	0.12(0.03)	0.17(0.03)	0.13(0.04)	0.17(0.03)	0.14(0.03)	0.17(0.04)	0.14(0.03)
Right double support time	0.13(0.04)	0.12(0.03)	0.17(0.03)	0.12(0.03)	0.17(0.03)	0.13(0.03)	0.17(0.04)	0.14(0.03)
Left toe in/out	-2.85(4.54)	-2.34(14.21)	-0.43(5.06)	4.9(10.02)	-0.68(5.13)	5.71(6.69)	-0.92(3.70)	4.22(8.99)
Right toe in/out	-2.56(3.67)	2.47(12.32)	-1.31(5.48)	6.81(6.86)	0.11(4.62)	7.02(7.40)	-0.04(4.05)	5.09(9.12)

Gait parameters of 4 year old children (n=15) for walking or running in four shod/unshod conditions.

	Barefoot Walk Mean (SD)	Barefoot Run Mean (SD	Sandal Walk Mean (SD)	Sandal Run Mean (SD)	Sneaker Walk Mean (SD)	Sneaker Run Mean (SD)	Boot Walk Mean (SD)	Boot Run Mean (SD)
Velocity (cm/s)	109.53(11.47)	329.15(24.59)	113.3(13.64)	312.99(16.54)	115.51(17.88)	314.04(33.32)	129.99 (55.44)	329.51(22.64)
Cadence	149.95(13.12)	251.61(9.93)	141.06(11.70)	236.59(12.85)	139.59(13.80)	239.08(10.13)	149.26(30.87)	239.63(9.91)
Left step time (s)	0.40(0.04)	0.24(0.01)	0.43(0.04)	0.26(0.01)	0.43(0.05)	0.25(0.01)	0.41(0.06)	0.25(0.01)
Right step time (s)	0.40(0.03)	0.24(0.02)	0.42(0.03)	0.25(0.02)	0.43(0.04)	0.25(0.01)	0.41(0.06)	0.25(0.01)
Left stride length (cm)	87.88(8.55)	157.78(11.34)	96.74(8.59)	160.38(12.79)	99.29(9.79)	157.17(15.76)	102.24(15.46)	165.85(11.79)
Right stride length (cm)	88.07(8.41)	158.68(12.61)	96.76(8.22)	158.51(12.47)	99.35(10.17)	158.41(15.89)	101.95(15.95)	164.83(9.89)
Left swing percentage (%)	41.60(1.10)	63.57(1.56)	40.7(0.86)	62.95(2.53)	40.59(1.27)	62.76(1.74)	42.28(6.06)	63.52(1.69)
Right swing percentage (%)	41.33(1.01)	63.56(2.23)	39.82(1.48)	62.56(2.85)	40.83(1.78)	62.86(2.28)	41.8(6.37)	63.89(1.93)
Left stance percentage (%)	58.42(1.10)	36.46(1.55)	59.29(0.85)	37.05(2.53)	59.39(1.27)	37.28(1.72)	57.69(6.06)	36.46(1.73)
Right stance percentage (%)	58.61(1.04)	36.44(2.24)	60.18(1.47)	37.4(2.83)	59.16(1.76)	37.12(2.26)	58.19(6.38)	36.13(1.93)
Left double support time	0.14(0.02)	0.13(0.02)	0.17(0.03)	0.13(0.03)	0.16(0.04)	0.13(0.03)	0.16(0.03)	0.14(0.02)
Right double support time	0.14(0.02)	0.13(0.02)	0.17(0.03)	0.13(0.03)	0.16(0.03)	0.13(0.02)	0.16(0.03)	0.14(0.02)
Left toe in/out	-1.3(5.77)	4.93(5.97)	2.08(5.56)	7.82(5.41)	-0.99(5.71)	5.91(4.29)	1.28(5.69)	6.23(5.79)
Right toe in/out	-1.53(8.03)	3.65(6.97)	1.36(5.73)	6.74(7.60)	0.37(6.53)	6.99(6.49)	1.2(5.51)	5.6(7.18)

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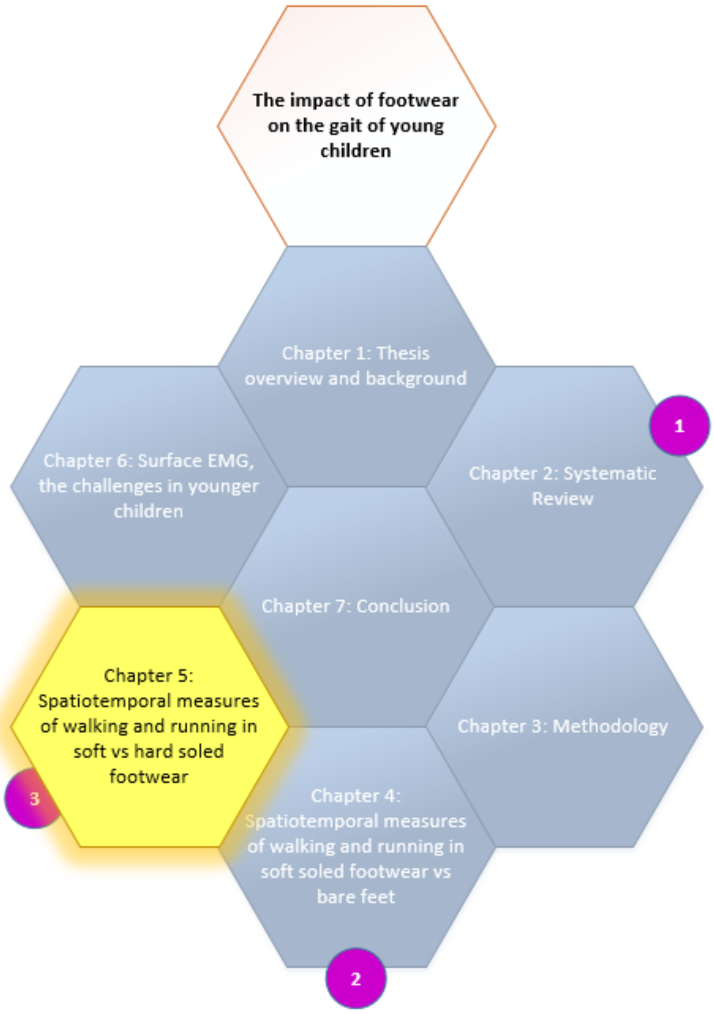
CHAPTER 5: A comparison of young children's spatiotemporal gait measures in three common types of footwear with different sole hardness

5.1 Preamble



Chapter 2 outlined the limited investigation of footwear impacts on young children's gait. Parents are often advised that young children should wear soft soled footwear when they are first beginning to walk independently, and then transition into footwear with a firmer sole. However, this advice is often not founded on evidence, as described in Chapter 2. In particular, the review highlighted the limited amount of research conducted in this area on the impact of different sole stiffness, in particular on younger children's gait. This limited exploration challenges parents and clinicians in making decisions for the child about this footwear feature. Therefore, this chapter investigates the differences in spatiotemporal measures of gait in children aged between 2-4 years, wearing three different types of footwear with a soft/flexible sole, and compare their gait while wearing a stiffer sole.

5.1.1 Publication- Under review

Cranage, S., Perraton L., Bowles KA., Williams C. (under review). A comparison of young children's spatiotemporal gait measures in three common types of footwear with different sole hardness (Gait & Posture).

5.2 Declaration for Thesis Chapter 5

In Chapter 5, the nature and extent of my contribution to the work was the following:

Nature of contribution	Extent of contribution
Author	70%

The following authors contributed to the work:

Name	Nature of contribution	Extent of contribution
A/Prof Cylie Williams	Co-author	10%
Dr. Kelly-Ann Bowles	Co-author	10%
Dr. Luke Perraton	Co-author	10%

Author contribution: All authors contributed to the review concept and design. **SC**: Conceptualisation, Methodology, Validation, Formal analysis, Investigation, Writing- Original draft. **CW:** Conceptualisation, Methodology, Validation, Formal Analysis, Investigation, Writing- Review and editing, Supervision, Funding acquisition. **LP:** Methodology, Validation, Investigation, Writing- Review and editing, Supervision. **KAB:** Conceptualisation, Methodology, Formal Analysis, Investigation, Writing- Review and editing, Supervision

Declaration by co-authors:

The undersigned hereby certify that:

(1) The above declaration correctly reflects the nature and extent of the candidate's contribution to this work, and the nature of the contribution of each of the co-authors.

(2) They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;

(3) They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;

(4) There are no other authors of the publication according to these criteria;

(5) Potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit

Signature 1	A/Prof Cylie Williams	Date: 09/12/2020
Signature 2	Dr. Kelly-Ann Bowles	Date: 0/02/2021
Signature 3	Dr. Luke Perraton	Date: 11/12/2020

5.3 Abstract

5.3.1 Background

It is unknown what the impact of sole hardness is on young children's gait. Yet, this feature is commonly marketed as having differing benefits for young children's walking and development.

5.3.2 Research Question

What are the differences in spatiotemporal measures of gait during walking and running in three common types of young children's footwear with a soft sole, compared to a hard sole?

5.3.3 Methods

The study used a quasi-experimental design, with the condition order randomised using a Latin square sequence. Forty-seven children were recruited (aged 2 - 4 years). Participants walked or ran the length of a GAITRite mat in a randomized order in a soft (Shore 48-53) or hard soled (Shore 60-65) sneaker, boot and sandal condition. Linear regression analyses were used to investigate the difference between footwear for the different gait parameters.

5.3.4 Results

Children walked with a shorter stride length in the hard-soled sandals compared to the soft-soled sandals ($p<0.05$). There were no other differences in spatiotemporal variables in the soft versus hard soled sandals during walking or running ($p>0.05$). There were no differences in any spatiotemporal gait variables during walking or running in soft versus hard-soled sneakers and no differences in walking or running in soft versus hard-soled boots ($p>0.05$).

5.3.5 Significance

There were few differences in spatiotemporal parameters between soft and hard-soled footwear in both walking and running in three different types of footwear. This may be a positive finding for footwear designers and manufacturers, as a harder sole appeared to have limited impact on spatiotemporal gait parameters.

Keywords: Shoes, footwear, gait, toddler, sole, shoe

5.4 Background

Footwear serves different purposes for younger children. When children are playing outdoors, footwear provides protection from surfaces and elements such prevention from lacerations, puncture wounds, infection or irritants [1]. The safety role footwear provides, therefore enables children to fully interact with their environment and build fundamental movement skills [1]. These skills are crucial for the progression of motor skill development and facilitates social participation with their peers [1, 2]. While there is no question of the protective role of footwear for children, little is known about any impact of different footwear features on the young and developing foot [3, 4].

During development, there are differences in foot structure and function in comparison to adults [5]. Young children's feet change over time with a number of structural adaptions that align with developmental stages such as growth rate, plasticity of the foot, and gross motor development [6, 7]. However, few studies have investigated the long-term impact of footwear type and hardness on foot health and function [8-10]. Health professionals commonly promote footwear having minimal impact on developing foot function or gross motor development [11].

These recommendations commonly start with the advice for young children to be barefoot or wear shoes with a soft sole, presuming they are ideal for foot development [12]. It is also often assumed that stiff and compressive footwear may have a negative impact on a young child's foot development [7, 11, 13]. However, there is limited empirical evidence supporting these theories. Designing longer term studies on the impact of footwear features or their gait impact on younger children are both costly and ethically challenging.

The impact of different types of footwear on immediate spatiotemporal variables, kinematics, kinetics, plantar loading and muscle activity have had limited investigation in children less than 6 years old [14-19]. In early walkers (walking less than 5 months), flexible footwear resulted in wider and shorter step length, with a reduced stance time compared to a stiffer shoe condition [13]. Children between the ages of 2-6 years also demonstrated some differences in spatiotemporal gait measures when walking in soft soled footwear compared to walking in barefoot [19]. These gait differences were similar in a variety of footwear with differing features, however these differences were minimised when running [19]. Soft soled footwear has no significant effect on spatiotemporal measures compared to a stiffer or harder sole shoe design in 7-9 year old children [17]. The limited research into the impact of different sole hardness on young children children's gait makes it difficult for parents and clinicians to make decisions about the importance of this footwear feature.

This study reports the results of the secondary aim in a larger study investigating different footwear sole features. The aim was to investigate the differences in spatiotemporal gait measures of children aged between two and four years, wearing three different types of footwear with softer or harder soles versions of each type of footwear. The secondary aim was to determine if there were differences between the footwear types in tripping frequency.

5.5 Methods

5.5.1 Study design

This research was approved by The Human Research Ethics Committee of Monash University, Victoria Australia (HREC/17/8549). All children participated with written parental consent, and where possible, the children provided verbal consent. A quasi-experimental design was used, with the condition order standardised through Latin square randomization. This study was nested within a larger trial (ACTRN12617000999336). This larger trial initially investigated the difference between soft/flexible sole footwear and barefoot walking and running in young children [19].

5.5.2 Participants and setting

There were 47 participants between two and four years of age (53% female). Parents of the participants reported no medical conditions, or previous medical history known to impact gait. Participants were recruited through social media platforms (Facebook, Twitter), and university newsletters. Data were collected at the Monash University gait laboratory, with all data collected for a single participant on the same day, in a single session.

5.5.3 Anthropometric and clinical measures

Anthropometric data collected included participant age, gender, height, weight, and footwear size. Body mass index (BMI) was calculated from the participants' height (cm) and weight (kg). Ankle dorsiflexion range of motion was measured during a weight bearing ankle lunge with the leg straight, and then with the knee bent with a goniometer [20]. Static foot posture was described with the Foot Posture Index-6 (FPI-6) [21]. Isometric knee extension/flexion and ankle dorsiflexion/plantarflexion strength (maximum voluntary isometric contraction: MVIC) were assessed with a Lafayette handheld dynamometer. Three trials were performed, and the peak trial was included in the analysis. All lower limb and foot measures were completed on the right leg only as previous literature has reported a high correlation between the left and right limb measures in non-pathological populations [22]. The lower limb measures were assessed by one of two clinicians (SC & CW), who both have extensive experience in assessing children's lower limb biomechanics, and routinely use these measures in clinical practice.

5.5.4 Gait assessment

A 4.3 metre GAITRite Electronic Walkway (CIR Systems Inc. Hvaertown, PA, USA) was used to assess spatiotemporal variables of participant's gait. This system has high reliability for gait measures in children [23]. Walking and running trials were completed at a self-selected speed, controlled during trials with a pacer walker (researcher who matched the gait of the child, and walked along side to minimize variation). The GAITRite set up had a 1.5 meter acceleration and deceleration run off at each end, limited by the size of the testing environment. Participants repeated each walking or running trial three times for each condition. Whenever a child deviated off the GAITRite mat, the entire condition was repeated until three full trials were completed on the mat.

5.5.5 Interventions

The footwear of interest were three different types of commercially available footwear that are commonly worn by young children: sandals, boots and sneakers. Footwear were provided by the study sponsor. Each style of footwear had differing sole shore hardness, with a soft/flexible sole (Shore A) and a harder sole (Shore B). Prior to dispatch from the factory, each sole was tested for uniform sole hardness by shoe manufacturer and a report provided to the research team. This ensured a consistent Shore A hardness of 48-53, marketed as a “soft sole” by the manufacturer, and considered soft/medium on the durometer shore hardness scale [24]. The comparative marketed “hard sole” was a Shore B (60-65), considered as a medium/hard on durometer scale [24]. The harder sole footwear shore was chosen by the study sponsor as outside the limit of sole hardness as feedback from parent focus groups.

The intervention footwear and their features were:

Sandals (Figure 22)*:*

- fully flexible, and open upper
- heel strap or small heel enclosure (depending on size) that had no stiffness
- adjustable ankle strap fastener to customise fit
- 7mm to 12mm heel stack height and 7mm to 9.5mm forefoot stack height
- weighed between 72g to 140g depending on size.

Figure 22 Sandal (Left: Shore A, Right: Shore B)

Sneakers (Figure 23)

- semi-firm and full enclosed heel counter
- Leather fully enclosed upper covering the top of the foot
- Two Velcro fasteners to customize fit
- single density sole with a 12mm to 17mm stack height, and an 11mm-12mm forefoot stack height
- weighed between 68g to 163g depending on size

Figure 23 Sneaker (Left: Shore A, Right: Shore B)

Boots (Figure 24)

- semi-firm and full enclosed heel counter
- Leather fully enclosed upper covering the top of the foot
- boot topline ended above the ankle with ankle zip and elastic to ease don and doffing
- single density sole 7mm to 12mm heel stack height and 7mm to 9.5mm forefoot stack height
- weighed between 75g to 160g depending on size.

Figure 24 Boot (Left: Shore A, Right: Shore B)

There were minimal variations in the different types of footwear in their sole shape and between sizes. The sole of each shoe was manufactured as a single unit, using the same material. There were differences in the size of the footwear varied from size 20EU to 30EU depending on the child's foot size.

5.5.7 Procedures

Prior to the testing appointment, parents were directed to the sponsor's website to determine the footwear size for their child. Footwear sizing was re-measured by a researcher at the beginning of the testing session to ensure appropriate fit and a different size of footwear provided if there was a fit concern. Children were encouraged to walk around the room, with footwear habituation being less than five minutes. A longer habituation time was not possible due to the study protocol and the data collection time frame for each child. No formal measure of prior typical footwear use was recorded for each child. All children were observed to be wearing footwear prior to the testing session.

Parents were emailed a visual procedural schedule for their child prior to the testing session. Parents were asked to show their child the visual schedule in preparation for the testing day. This provided the child with familiarity of the space and the requirements of them on the day of testing. On the day, children walked through the process with a reward chart. As each child completed each testing component, they were given a stamp to visualize task progression, and a sticker as a reward on completion of the testing.

As part of the orientation, children practiced a walk or run pace and a researcher walked along side to match and attempt to standardize participants' speed between trials. Once familiar, each child walked or ran the length of the GAITRite mat in a randomized order in a soft and hard soled footwear condition (sandal, boot and sneaker). They were supported to keep on the GAITRite mat through positive verbal encouragement between trials. The researchers alternated the side they walked or ran beside the child dependent on where parents were standing in the room. A post box was set up at the end of the mat and majority of children carried a small letter or token to post. The small items were able to be carried in one hand, were small in size and weight, therefore thought to have minimal effect on the child's gait. Carrying tokens were inconsistent between children, with some preferring not to or some alternating their carrying hands throughout testing. Visual markers were placed on the sides of the mat and they were encouraged to stay inside the markers to ensure gait centring on mat for data collection.

The number of trips or stumbles were also recorded to determine if any condition resulted in increased number of trips during testing. A stumble was defined as the toe contacting the ground during swing phase of gait, initiating a loss of footing. A research team member who walked alongside the participant visually observed the tripping and this was manually recorded by a second researcher.

5.5.8 Data Analysis

Data were analysed in Stata 13 [25]. All footprints were visualized within the software at time of testing, and any partial footprints removed prior to analysis. A trial was counted if the child stayed on the mat, for majority of the length of the mat, and completed three full lengths of the GAITRite.

Linear regression analyses, clustered by participant, were used to investigate the main effect of soft-soled versus hard soles in each of the footwear types. Data were clustered by individual participants during analysis and robust variance estimates were used to account for the within-subject nature of the study design. This method of analysis meant that normalization of different leg length was unnecessary. Effect sizes (ES) were calculated using the mean difference between the footwear conditions and dividing this by the pooled standard deviation. Effect sizes were calculated as small (<0.6), medium (0.61-1-19), or large ($\geq$1.2)[26]. Results were considered statistically significant where $p<0.05$. A sample size was calculated based on the primary aim comparing the step length of children wearing footwear compared to walking in bare feet. This analysis determined a sample size of 30 children was required to achieve 80% power with a minimum effect size of 0.53 as a result of the difference in shod walking conditions of step length using an alpha criterion of 0.05 [14].

5.6 Results

Demographic data of participants have been published [19] and participants had similar ankle range of motion, FPI-6 and strength measures as previous published data of typically developing children (Table 10) [27].

Table 10 Anthropometric data

	All children (N= 47) Mean (SD) or N (%)	2 year olds (n=15) Mean (SD) or N (%)	3 year olds (n=17) Mean (SD) or N (%)	4 year olds (n=15) Mean (SD) or N (%)
Completed trials		9 (60%)	14 (82%)	14 (93%)
Partial trials		6 (40%)	3 (18%)	1 (7%)
Gender (Female)	25 (53%)	7 (47%)	10 (59%)	8 (53%)
Height (cm)	99.51 (6.84)	92.70 (3.25)	99.42 (4.88)	106.44 (3.83)
Weight (kg)	16.58 (2.28)	14.69 (1.90)	16.46 (1.67)	18.6 (1.41)
BMI Kg/m^2	16.66 (1.33)	17.05 (1.84)	16.61 (1.67)	16.35 (0.83)
Ankle ROM – Knee extended (degrees)	33.1 (3.9)	32.7 (3.2)	32.7 (3.9)	34.0 (4.5)
Ankle ROM – Knee bent (degrees)	41.7 (4.8)	42.8 (5.4)	38.5 (4.2)	44.3 (2.8)
FPI-6 (Right only)	4.21 (1.36)	4.80 (0.94)	3.88 (1.58)	4.00 (1.46)
Hamstring strength (N)	45.65 (13.17)	34.43 (11.02)	41.43(7.63)	55.76(10.18)
Quadriceps Strength (N)	67.16 (22.20)	46.17 (17.26)	68.01 (19.45)	83.08(14.72)
Gastrocnemius/Soleus Strength (N)	71.20 (24.52)	51.26(21.54)	71.65 (23.81)	82.17 (12.67)

The spatiotemporal gait variables comparing walking and running in soft versus hard-soled sandals are displayed in Table 11. Children walked with a left and right shorter stride length in the hard-soled sandals (Mean (standard deviation (SD)) of 82.91 (11.76) cm versus 82.97 (11.99) cm respectively) compared to soft soled sandals (Mean (SD) 84.98 (13.02) cm and 85.01 (12.80) cm respectively), with a small effect size at the left and right respectively (d=0.17 and d=0.16*)*. There were no differences in other spatiotemporal variables including; velocity, cadence, step time, swing percentage, stance percentage, double support time or the toe in/out angle of the left and right foot (p>0.05). There were no differences seen across any of the variables between soft and hard sandals while running (p>0.05). There were small effects of sole hardness on walking for all variables (d<0.25), less for running (d<0.019).

There were no statically significant differences in any spatiotemporal gait variables during walking or running in soft versus hard soled sneakers (p>0.05) (Table 12). There were small effects of sole hardness on walking in all variables (d<0.22) and when running (d<0.28)

Lastly, there were no statically significant differences in walking or running in soft versus hard-soled boots (p>0.05) (Table 13). Similar to sneakers, there were small effects of sole hardness on walking in all variables (*d*<26) and when running (0.27).

There were 17 stumbles across all trials. Stumbles were more frequent during walking conditions (n=16) compared to running conditions (n=1), soft-soled footwear (n=12) compared to hard-soled (n=5), and in sandals (n=10) compared to sneakers (n=5) and boots (n=2).

Table 11 Sandals: Comparison of spatiotemporal variables during walking and running for all participants (2,3 and 4-year-olds)

	Soft-sole Mean (SD)	Hard-sole Mean (SD)	Soft versus hard-sole Coef [95% CI][28], p value	Effect size (*d*)	Soft sole Mean (SD)	Hard sole Mean (SD)	Soft versus Hard-sole Coef [95% CI], p value	Effect size (*d*)
	WALKING				Running			
Velocity (cm/sec)	101.50(18.74)	97.97(18.45)	-3.53 [-7.50, 0.43], 0.08	0.19	266.28(52.86)	264.37(51.21)	-1.92 [-7.20, 11.03], 0.67	0.04
Cadence (steps/min)	143.63(14.61)	141.97(15.99)	-1.66 [-5.20, 1.87], 0.35	0.11	239.01(16.16)	239.95(14.84)	0.94 [-4.89, 3.02], 0.64	0.06
Left step time (sec)	0.42(0.05)	0.43(0.05)	0.01 [-0.01, 0.02], 0.31	0.20	0.25(0.02)	0.25(0.02)	0.00 [-0.00, 0.01], 0.46	0.00
Right step time (sec)	0.42(0.05)	0.43(0.05)	0.01 [-0.01, 0.02], 0.37	0.20	0.25(0.02)	0.25(0.02)	0.00 [-0.01, 0.00], 0.94	0.00
Left stride length (cm)	84.98(13.02)	82.91(11.76)	-2.07 [-4.07, -0.08], 0.04	0.17	134.72(28.24)	133.15(26.31)	-1.56 [-2.21, 5.34], 0.41	0.06
Right stride length (cm)	85.01(12.80)	82.97(11.99)	-2.04 [-4.06, -0.03], 0.04	0.16	134.37(27.87)	132.89(26.05)	-1.49 [-2.41, 5.38], 0.45	0.05
Left swing percentage (%)	39.88(2.08)	39.89(1.70)	0.01 [-0.46, 0.48], 0.96	0.01	60.83(3.93)	60.27(4.01)	-0.55 [-0.14, 1.25], 0.12	0.14
Right swing percentage (%)	39.73(2.15)	39.47(2.01)	-0.26 [-0.81, 0.28], 0.34	0.12	60.90(4.11)	60.12(4.26)	-0.78 [-0.05, 1.60], 0.07	0.19
Left stance percentage (%)	60.11(2.09)	60.10(1.70)	-0.01 [-0.48, 0.45], 0.96	0.01	39.17(3.91)	39.73(4.03)	0.56 [-1.26, 0.14], 0.11	0.14
Right stance percentage (%)	60.28(2.13)	60.55(2.00)	0.26 [-0.27, 0.80], 0.33	0.13	39.08(4.11)	39.89(4.24)	0.81 [-1.64, 0.02], 0.06	0.19
Left double support time (sec)	0.17(0.04)	0.18(0.04)	0.01 [-0.00, 0.02], 0.27	0.25	0.11(0.04)	0.11(0.04)	-0.01 [-0.00, 0.01], 0.10	0.00
Right double support time (sec)	0.17(0.04)	0.18(0.04)	0.00 [-0.01, 0.01], 0.58	0.25	0.11(0.04)	0.11(0.04)	-0.00 [-0.00, 0.01], 0.15	0.00
Left toe in/out (degree)	1.14(5.21)	0.94(4.30)	-0.20 [-1.34, 0.94], 0.72	0.04	5.53(7.30)	4.23(6.83)	-1.30 [-0.20, 2.80], 0.09	0.18
Right toe in/out (degree)	0.71(5.76)	0.85(5.39)	0.14 [-1.13, 1.40], 0.83	0.03	6.68(6.77)	5.89(6.77)	-0.78 [-0.71, 2.28], 0.30	0.12

Table 12 Sneakers: Comparison of spatiotemporal variables during walking and running for all participants (2,3 and 4-year-olds)

	Soft-sole Mean (SD)	Hard-sole Mean (SD)	Soft versus Hard-sole Coef [95% CI], p value	Effect size (*d*)	Soft-sole Mean (SD)	Hard-sole Mean (SD)	Soft versus Hard-sole Coef [95% CI], p value	Effect size (*d*)
	WALKING				RUNNING			
Velocity (cm/sec)	102.68(19.80)	104.21(19.75)	1.52 [-2.55, 5.61], 0.45	0.08	275.83(50.72)	273.51(48.65)	-2.32 [-7.83, 3.18], 0.40	0.05
Cadence (steps/min)	141.41(14.16)	143.06(13.09)	1.66 [-1.69, 5.0], 0.32	0.12	239.38(12.43	237.00(12.04)	-2.38 [-6.36, 1.61], 0.24	0.19
Left step time (sec)	0.43(0.05)	0.42(0.04)	-0.00 [-0.02, 0.01], 0.38	0.22	0.25(0.01)	0.26(0.02)	0.00 [-0.00, 0.01], 0.24	0.27
Right step time (sec)	0.43(0.05)	0.42(0.04)	-0.01 [-0.02, 0.00], 0.19	0.22	0.25(0.02)	0.25(0.02)	0.00 [-0.00, 0.01], 0.36	0.00
Left stride length (cm)	87.12(13.07)	87.42(13.85)	0.30 [-1.65, 2.25], 0.76	0.02	138.42(25.39)	139.91(26.77)	1.49 [-1.70, 4.68], 0.35	0.06
Right stride length (cm)	87.05(13.15)	87.45(13.54)	0.40 [-1.64, 2.43], 0.70	0.03	139.18(25.52)	139.15(26.99)	-0.03 [-3.63, 3.57], 0.99	0.00
Left swing percentage (%)	39.9(1.47)	40.16(1.46)	0.26 [-0.20, 0.72], 0.26	0.18	62.16(3.00)	62.27(3.51)	0.11 [-0.60, 0.82], 0.77	0.03
Right swing percentage (%)	39.98(1.65)	39.97(1.90)	-0.01 [-0.55, 0.54], 0.98	0.01	62.19(3.45)	62.20(3.57)	0.01 [-0.83, 0.85], 0.98	0.00
Left stance percentage (%)	60.10(1.46)	59.84(1.45)	-0.26 [-0.71, 0.20], 0.26	0.18	37.86(2.98)	37.74(3.51)	-0.12 [-0.83, 0.59], 0.73	0.04
Right stance percentage (%)	60.02(1.65)	60.02(1.91)	0.01 [-0.54, 0.55], 0.98	0.00	37.82(3.43)	37.79(3.60)	-0.03 [-0.87, 0.82], 0.95	0.01
Left double support time (sec)	0.17(0.04)	0.17(0.04)	-0.00 [-0.01, 0.01], 0.43	0.00	0.13(0.04)	0.13(0.04)	0.00 [-0.01, 0.01], 0.52	0.00
Right double support time (sec)	0.17(0.04)	0.17(0.04)	-0.01 [-0.02, 0.00], 0.16	0.00	0.12(0.03)	0.13(0.04)	0.01 [-0.00, 0.01], 0.15	0.28
Left toe in/out (degree)	-0.72(5.11)	-0.82(4.98)	-0.10 [-1.14, 0.94], 0.85	0.02	5.54(5.29)	4.01(7.96)	-1.53 [-3.48, 0.42], 0.12	0.23
Right toe in/out (degree)	0.61(5.17)	0.43(4.96)	-0.19 [-1.02, 0.65], 0.65	0.04	6.59(6.42)	5.86(7.08)	-0.74 [-2.22, 0.75], 0.32	0.11

Table 13 Boots: Comparison of spatiotemporal variables during walking and running for all participants (2,3 and 4-year-olds)

	Soft-sole Mean (SD)	Hard-sole Mean (SD)	Soft versus hard-sole Coef [95% CI], p value	Effect size (*d*)	Soft-sole Mean (SD)	Hard-sole Mean (SD)	Soft versus hard-sole Coef [95% CI], p value	Effect size (*d*)
	WALKING				RUNNING			
Velocity (cm/sec)	107.53(37.28)	102.15(20.29)	-5.38 [-15.44, 4.67], 0.29	0.18	275.03(56.70)	275.86(54.97)	0.83 [-3.85, 5.50], 0.72	0.01
Cadence (steps/min)	144.95(20.61)	140.22(15.15)	-4.72 [-10.63, 1.18], 0.11	0.26	239.66(12.41)	238.59(13.17)	-1.07 [-3.95, 1.81], 0.46	0.08
Left step time (sec)	0.42(0.05)	0.43(0.05)	0.01 [-0.00-0.03], 0.12	0.20	0.25(0.01)	0.26(0.02)	0.00 [-0.00, 0.01], 0.08	0.27
Right step time (sec)	0.42(0.05)	0.43(0.05)	0.01 [-0.00, 0.03], 0.06	0.20	0.25(0.02)	0.25(0.02)	-0.00 [-0.01, 0.00], 0.33	0.00
Left stride length (cm)	88.01(15.78)	87.45(13.17)	-0.58 [-4.10, 2.99], 0.75	0.04	138.35(28.61)	140.12(28.68)	1.77 [-0.38, 3.91], 0.10	0.06
Right stride length (cm)	87.80(15.82)	87.33(13.14)	-0.47 [-4.01, 3.06], 0.79	0.03	138.32(28.32)	138.82(27.97)	0.49 [-1.63, 2.62], 0.64	0.02
Left swing percentage (%)	40.6(4.03)	40.16(1.71)	-0.44 [-1.62, 0.75], 0.46	0.14	61.8(3.64)	62.24(3.84)	0.44 [-0.06, 0.94], 0.08	0.12
Right swing percentage (%)	40.42(4.18)	40.20(1.77)	-0.22 [-1.36, 0.91], 0.69	0.07	62.08(3.98)	61.78(3.82)	-0.30 [-0.90, 0.30], 0.32	0.08
Left stance percentage (%)	59.4(4.03)	59.86(1.72)	0.46 [-0.73, 1.64], 0.44	0.15	38.22(3.62)	37.76(3.83)	-0.46 [-0.95, 0.02], 0.06	0.12
Right stance percentage (%)	59.58(4.18)	59.8(1.77)	0.22 [-0.92, 1.35], 0.70	0.07	37.93(3.98)	38.21(3.84)	0.28 [-0.32, 0.88], 0.36	0.07
Left double support time (sec)	0.17(0.04)	0.17(0.04)	0.00 [-0.01, 0.01], 0.90	0.00	0.12(0.04)	0.12(0.04)	0.00 [-0.00, 0.01], 0.54	0.00
Right double support time (sec)	0.17(0.04)	0.17(0.04)	0.00 [-0.01, 0.01], 0.89	0.00	0.12(0.04)	0.13(0.04)	0.00 [-0.00, 0.01], 0.45	0.25
Left toe in/out (degree)	0.27(4.59)	0.29(4.67)	0.02 [-1.07, 1.12], 0.97	0.00	4.51(6.92)	5.33(6.79)	0.82 [-0.91, 2.54], 0.34	0.12
Right toe in/out (degree)	1.01(4.91)	0.92(4.96)	-0.09 [-0.84, 0.65], 0.80	0.02	5.20(7.57)	6.36(7.42)	1.16 [-0.49, 2.81], 0.16	0.15

5.7 Discussion

To our knowledge, this is the first study undertaken in children of this age group with commercially available footwear of near identical footwear components, but with differing sole hardness. There were no differences seen across all spatiotemporal variables in walking and running in all footwear types, other than the shorter stride length in the hard-soled sandals. Finding few differences across all of the spatiotemporal parameters between soft and hard-soled footwear (sneakers, sandals and boots) in both walking and running was unexpected. It is unknown if the observed differences in step length were due to immaturity in gait, as these changes differ to those observed in older children [13, 17, 29]. It is possible that as a child develops gait maturity and their gait is less variable, they may be more sensitive to factors such as footwear. Therefore, the sole hardness may have had less of an influence on the spatiotemporal parameters during walking and running in this age group. While all of these children within the study were independently walking for longer than 12 months, it is possible that they adapted to differing sole hardness with less changes to the gait parameters compared to the earlier walkers [13] and the older children [17, 29]. Similarly, the differences that were observed may be related to the individual weight of the child and their ability to push through a sole that is harder. The heavier the child, the more their weight may limit any impact of footwear sole stiffness.

The shorter stride length in hard sandals compared to soft sandals, but not other footwear was an interesting finding. While it could be expected that a harder sole may have created an increased resistance to bend in the shoe and therefore may have contributed to the shoe propping the foot into more of a rigid unit. This effect has been previously described by other researchers as a mechanism of potential footwear action or support for the midfoot [29]. While we might expect a rigid unit to increase the push off force generated at toe off, and therefore increase stride length, this was not the case. This may be more of a result of the footwear upper having less fixation. Therefore, less fixation had more of an impact than the flexibility of the sole. In spite of this, the effect sizes were small, therefore presumably has minimal clinical relevance.

In addition to the stride length difference, the soft-soled sandals also resulted in more stumbles compared to the other styles of footwear. Stumbles were more frequent during walking trials compared to running, and in soft soled footwear compared to hard soled footwear. While sandals had some form of adjustability at the front of the foot, this was not fully customizable to all children. Some children's feet were also too narrow for even the most customised buckle fixture. Therefore, this may have resulted in increased movement at the front of the foot in the footwear. While toe clearance was not measured during this study, the rigidity (or lack thereof) may have impacted this clearance or changed the perception of clearance depending on the flexibility of the sole. Measurement of toe clearance should be considered in future research of children's commercially available footwear, particularly if the footwear is being considered as a therapeutic aid.

The findings from this research cannot be extrapolated to clinical recommendations for transitioning timing of a young child from soft to harder soled footwear. The study found minimal differences between hard and softer soled footwear on spatiotemporal variables in children's gait. Therefore, this limited impact of sole hardness during walking and running may assist footwear manufacturers establish upper sole hardness limits during the design process to support the robustness of the footwear sole. This has durability and cost implications for parents. It is also possible though that the difference in shore hardness deemed by the sponsor as outside the range of what they would consider manufacturing based on parent feedback, was not great enough to impact gait change. Shore hardness has the potential to also impact on comfort and this should be considered in future research of determining upper limits of hardness, or lower limits of softness in contrast with durability.

The artificial testing environment should be considered as a limitation of this research. Children have been observed to perform differently in a laboratory environment, the limited environmental challenges do not mimic real life [30]. Deviations to real life activity were mitigated by the extensive paediatric experience of the research team, however the laboratory gait lab environment was new to the participants and artificial construct of straight line walking, that is not always common to young children [31]. While the GAITRite has a high reliability for gait walking measurements of children, there are limited reliability studies for running in children therefore this may have increased the variability of each child's trial. Future research should consider testing the reliability of running in young children on the GAITRite. Also, any links between sole hardness, upper fixations and comfort on functional ability should be further explored.

5.8 Conclusion

There were few differences in spatiotemporal parameters between soft/hard-soled footwear and footwear types in both walking and running young children. This may have positive benefits for footwear manufacturers and parents. With increased robustness of the sole of the footwear, there may be increased durability and a cost benefit. As a result of this study, clinicians may consider reassuring parents of the minimal difference in sole hardness between commercially available footwear in terms of spatiotemporal parameters. Further research is required into the impact of sole hardness and upper interface on functional gross motor impact and comfort in young children This would benefit our understanding of any potential therapeutic role footwear may play where there are foot or ankle problems in children.

Declarations

Ethics approval and consent to participate

The Human Research Ethics Committee of Monash University, Victoria Australia approved this research (HREC/17/8549). Parents of included children provided written consent, and all children assented to participate.

Consent for publication

Not applicable

Availability of data and material

Please contact author for data requests

Declaration of interest

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Credit author statement

SC: Conceptualisation, Methodology, Validation, Formal analysis, Investigation, Writing- Original draft. **CW:** Conceptualisation, Methodology, Validation, Formal Analysis, Investigation, Writing- Review and editing, Supervision, Funding acquisition. **LP:**

Methodology, Validation, Investigation, Writing- Review and editing, Supervision. **KAB:** Conceptualisation, Methodology, Formal Analysis, Investigation, Writing- Review and editing, Supervision

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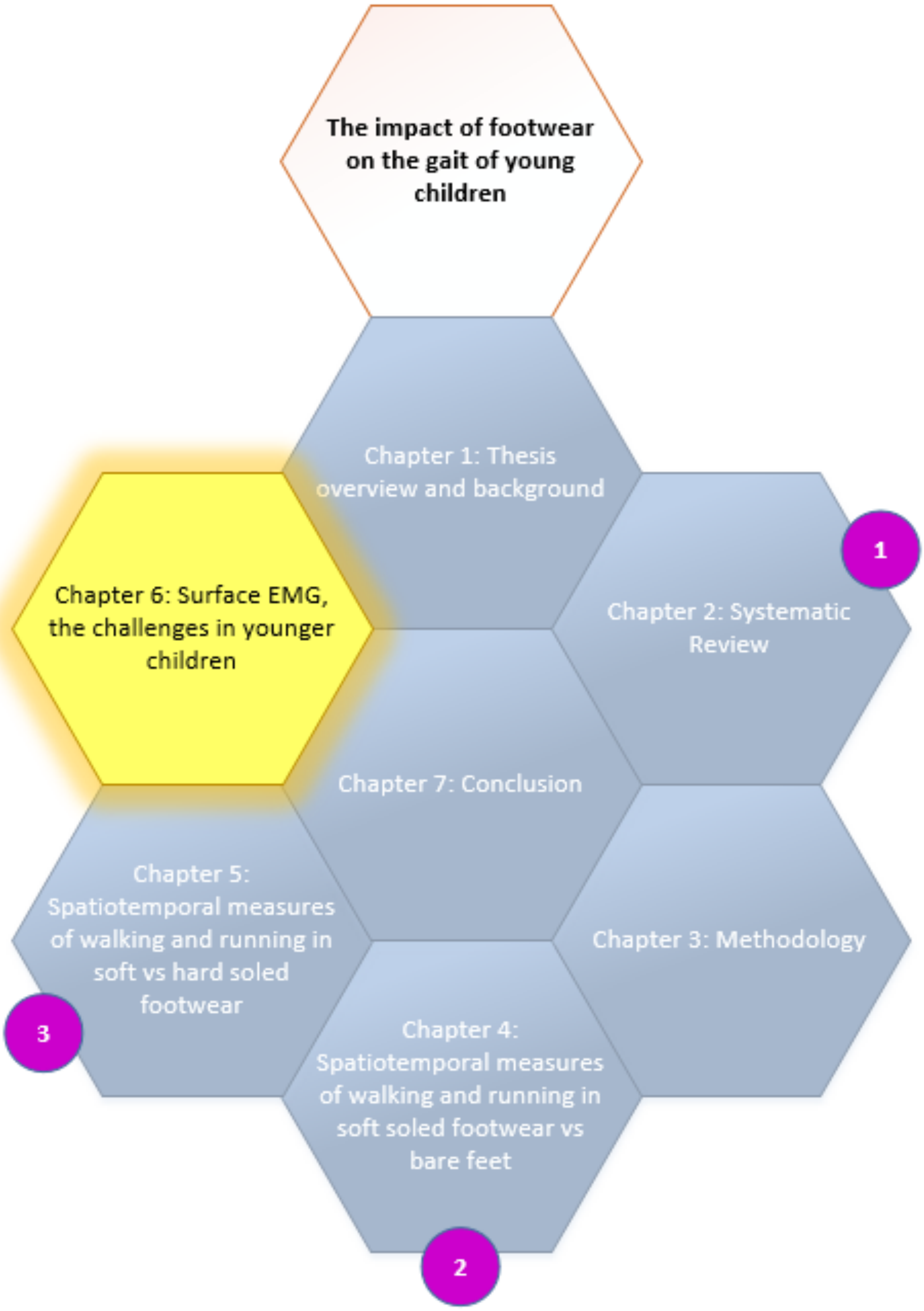
CHAPTER 6-EMG- Little steps, the challenges of EMG in early walkers

6.1 Preamble



This chapter will discuss the reason why it may be important to investigate muscle activation patterns in children during gait. Assessing muscle activation patterns in children during gait is important because it provides insight into mechanisms of changes or differences in movement patterns, however collecting data from children using surface electromyography

(EMG) is notoriously difficult. Acknowledging these limitations, the purpose of this chapter was to:

i) Describe the experience of collecting surface EMG data in young children to inform future investigations, including the challenges faced.

ii) Determine the feasibility of collecting surface EMG data with young children (including rate of successful data collection and quality of data)

iii) Describe the results of data collection in light of warranting further investigation.

This chapter consists of background of surface EMG and previous studies that have been completed using surface EMG in gait analysis in younger children. It includes the study aims and methods and a description of data collection results. In addition, this chapter provides a discussion of the challenges faced including sensor attachment, size and placement, use of a footswitch and amplitude data to inform future research.

6.2 Background

6.2.1 Muscle contractions

Muscle contractions initiate the sliding of actin and myosin causing a muscle to contract and relax (1). The motor neuron (cell body, dendrites and an axon) is projected from the ventral horn of the spinal column to the skeletal muscle and forms synapses with muscle fibres. A motor unit is made up of a motor neuron and the skeletal muscle fibres innervated by that motor neuron's axonal terminals. When groups of motor units are activated, they work together to coordinate the contraction of a single muscle. Each firing of the motor unit produces a force twitch in its motor unit (2, 3). When force twitches occur in close enough succession they produce a sustained force, which allows us to move our limbs, breathe or circulate blood around the body (1).

6.2.2. Electromyography (EMG)

The nervous system controls the aforementioned muscle activity (contraction/relaxation) which is dependent on the anatomical and physiological properties of muscles (4). An electromyography (EMG) signal is a measure of the electrical activity of the muscle's motor units. The EMG signal measures electrical currents generated in muscles during its contraction which represents neuromuscular activities (4). Motor unit action potentials are responsible for the muscle contraction. The EMG signal is based upon action potentials of the muscle fibre membrane which results in depolarisation and repolarisation processes as described above. EMG can consist of two types: surface EMG and intramuscular EMG (4, 5). During surface EMG measurement, the signal is collected using electrodes applied to the skin surface, whereas intramuscular EMG is more invasive, and involves electrodes being applied within the muscle belly.

6.2.3. Surface electromyography (sEMG) in gait analysis

Surface EMG is a non-invasive way of measuring electrical activity within a muscle during its activation and relaxation cycle (6). Surface EMG electrodes are applied to the skin over the muscle belly of interest and record motor recruitment timing and the intensity of force produced (7). When measuring muscle activation, the aim is to determine if any muscles in the vicinity of the sensor are active or not. It works best on superficial muscles with less adipose tissue surrounding the muscle being assessed.

Surface EMG is a useful method during gait analysis to obtain information of muscular function during walking (8). It can be used for a number of different reasons, including supporting clinicians with an objective assessment of muscular function during dynamic gait. It can also provide information on neural control during walking, any spasticity or co-contraction in pre surgical treatments. Surface EMG can also play a role in evaluating if a treatment has been effective. For example, this can include evaluation of muscle activity while wearing ankle foot orthoses. Surface electromyography allows us to study muscle activity non-invasively and to evaluate the timing of muscle activation during movement (9). It can measure a number of different things including muscle force (isometric contractions), muscle activation timing (On/Off) or the fatigue index of a particular muscle. It can also compare the behaviour of different muscles including the relative amount of contribution, co-activation and pattern identification (6).

An important component of surface EMG is the placement of sensors on the muscle. The close vicinity of other active muscles can increase the risk of cross talk signals (signal detected from a nearby muscle). This risk of often higher in children as there is potential for cross talk from adjacent muscles due to the smaller circumference of the limbs of children (20).

6.2.4. Previous research sEMG and footwear in younger children

Reference datasets about surface EMG have been developed in younger and school aged children (8, 10-12). One study developed a normative dataset of muscle activation patterns across a large number of strides from 100 healthy children (8). This research focused on determining the onset and offset instants for each of the observed muscles with the use of a footswitch, knee goniometer and surface EMG. The results from the large number of strides determined each child used a specific muscle with different activation modalities, even during the same walk. The study found various activation patterns to assist in clinical gait analysis and was published as a reference in the design of future gait studies (8). However, there are limited studies that have explored the impact of footwear and muscle activation patterns measured with surface EMG, particularly in younger children (13).

6.2.5. Maximum voluntary isometric contraction (MVIC)

The most common method of normalising EMG signals from a particular muscle is the use of the maximum voluntary isometric contraction (MVIC) from the same muscle as the reference value for comparison (14). This is often used during surface EMG studies to assess the force produced in a muscle, in addition to the onset or timing of muscle contractions. MVIC is a manual muscle test to produce the maximum contraction in the muscle of interest, which is completed as a single-joint isometric exertion against a static resistance (15). It has been suggested that the test requires at least 3 repetitions to be performed, separated by 2 minutes to reduce any effects of fatigue (15). The maximum value obtained from the MVIC allows for the level of activity of the muscle of interest compared to its maximal activation capacity (16).

Repeatability of the MVIC requires guidance of the subjects with a set protocol for each muscle group, performing the tests the same way with each repetition. The participants are also required to be familiar with producing a maximum effort, allowing adequate time in between tests to avoid fatigue. While research has shown reliability of measuring foot and ankle muscle strength with a hand held dynamometer in younger children aged 2-4 years (17), there is limited evidence on the reliability of MVIC in this age group for the purpose of surface EMG.

6.3 Aims

The primary outcome of our study was to measure the spatiotemporal measures of gait and has been addressed in Chapters 4 and 5. This presented a unique opportunity to collect data on such a large cohort of young children. With a paucity of literature in this area (13), a secondary aim was to investigate if muscle activity during walking and running in different types of footwear can be measured via surface EMG in younger children? This was addressed in the thesis with the following:

i) Describing the experience of collecting surface EMG data with younger children to inform future investigations

ii) Determining the feasibility of collecting surface EMG data with young children

iii) Describing the results of data collection

6.4 Methods

6.4.1. Muscle groups

In addition to the methods referred to in Chapter 3, small sensors were placed on the key muscle groups, lateral gastrocnemius, biceps femoris and rectus femoris (Figure 25) using the Trigno™ system (Delsys Inc, Massachusetts, USA) (18).

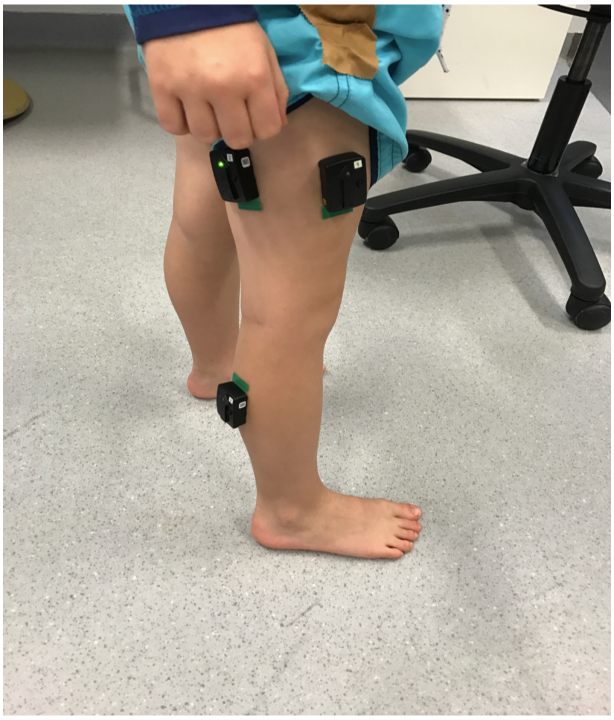


Figure 25 EMG sensor placement

These muscle groups were selected by the research team due to the size of the sensors, to reduce the chance of cross talk between smaller muscle groups. Hypoallergenic tape was applied over the sensors to keep them in place. When the participant started walking, the “start” button was clicked and the “stop” button when they reached the end of the mat. This protocol aimed to avoid collection of gait initiation data and the period of slowing down known to produce variations in the EMG signals (18). Five children (n=15) from each age group (2, 3 and 4 year olds) were randomly selected to complete surface EMG in all footwear conditions previously mentioned in Chapter 3.8.

6.4.2. Data Analysis of Gait in EMGworks Analysis

A new workplace was created using the Delsys software (18). The raw EMG signal data was visually inspected, and each muscle group was selected and plotted as a subplot.
The Y axis was autoscaled and the mean was removed from the data. Following this, an enveloped EMG signal was produced, and a Root Mean Square (RMS) calculation completed, leaving a subplot of Root Mean Square EMG signals. The RMS calculation provides the most insight into the amplitude of the EMG signal since it gives a measure of the power of the signal (18). From this data, the maximum y value was taken (Y value as taken from 3 consecutive steps in each of the footwear conditions) through visual observation. As a footswitch was not used to collect the data, we were unable to define clear heel strike events within the gait cycle. Cyclical analysis (defined events which can be used to plot the mean and standard deviation of multiple cycles) (18) was unable to be extracted and therefore EMG timings were unable to be analysed.

6.5. Results

A detailed description of the experience and factors affecting the feasibility collecting surface EMG data during gait with young children follows in section 6.6. Data were collected from 9 children. This was less than planned within our protocol of 15 children. Data from six children was not able to be collected and analysed due to the children removing the sensors during testing or difficulty with applying the sensors at the beginning of the study.

For our secondary aim, there was a pragmatic approach of attempting to collect EMG data from 15 participants based on availability of resources. As a result of these challenges, data was unable to be adequately analysed to determine if there were any differences observed in muscle activity in the different footwear types and Shore hardness. While this provided insufficient data that could be interpreted and analysed, our work did produce feasibility findings, adding to the overall structure of this thesis.

The EMG results were variable and difficult to interpret as there were vast individual variations in output, therefore further analyses (timing, magnitude) were not possible. There was a possibility that some of these differences may have been attributed to the child's age, and differences in the typical variations seen at different developmental stages of children (19). The large visual variability in our data potentially demonstrated that every child recruited muscles differently. However due to the difficulties of collecting this data and inability to use a footswitch, we were not confident that these results were an accurate representation of each child.

6.6 Exploring the challenges

6.6.1. Sensor attachments

The sensors that were placed on the children were probably more distracting for the younger child than we had originally anticipated. We observed many children attempting to remove the sensors at many opportunities and due to distraction, were visually observed to change their gait pattern significantly. While this was something that was not measured, visual observation throughout testing included children ceasing walking or running mid trial, moving their centre of gravity to bend down in an attempt to remove the sensors or refusal to go on with the trial.

We attempted to place surface EMG on the children with stories and engaged the children with play. However, we are not confident in generalising the EMG data to other children because of violations in the testing protocol (as expected in young children) which resulted in data variability. It is therefore difficult to say if the variability in the results is a result of gait immaturity or the changes that children made as a result of their adherence. Surface anatomy also needs to be considered with the size of the muscle belly in relation to the area of the electrode. Therefore, we may not be confident that that muscle belly is that muscle belly we set out to measure or if there was any interference from surrounding muscles.

6.6.2. Sensor size and placement

To reduce the likelihood of cross signal talk from nearby muscles, electrodes should be placed in the midline of the muscle belly (18). The most validated recommendations come from the Surface Electromyography for the Non-Invasive assessment of muscles (SENIAM), which has attempted to standardise surface EMG placement (20). This includes starting postures, sensor placements and clinician testing to ensure the correct muscle and muscle placement is completed. Due to the young age of the children within our study, a standardised way of applying the sensors was particularly difficult.

We could not be confident that we were recording muscle activity from the muscle we were trying to assess, or if there was a cross signal from nearby muscles due to the small size of the muscle groups being tested in this cohort of children. While we attempted to ensure this did not occur by visually observing the raw EMG data, we cannot be confident in our results. These results reduce our confidence that surface EMG can be collected in this cohort age group, or with this particular system.

6.6.3. Use of a footswitch

The detection of the timing of a gait phase in surface EMG is most common with the use of a foot switch. Foot switches are able to detect clear heel strike events during a gait cycle, and subsequently can be divided into strides, identifying the start and end of each gait cycle (18, 21). As EMG was always the secondary outcome in our study, a footswitch was not used within this study. As we did not want to negatively affect our primary outcome measure, compromises had to be made. It was decided by the research team that adding a footswitch would have created potential adaptation in a younger child’s gait that may devalue our other gait parameters of interest.

A footswitch is required to be attached to the feet or innersole of the shoe or a child's bare feet, generally at the heel, first metatarsal and fifth metatarsal (22). We felt this addition would have changed the gait of a young child significantly. This was confirmed during analysis by their responses in trying to remove the larger EMG sensors. The additional weight of the footswitch (19g) may have also caused additional gait changes in a smaller child. Footswitch use is additionally challenging in children as the equipment is often scaled to adult foot sizes. In previous studies with children aged 6-11 years (8) three footswitches (size 10mm x 10mm x 0.5mm) were attached beneath the heel, first and fifth metatarsal heads of each foot. An older child potentially responds differently with adaptations than that of a younger child without any interference from the footswitch.

6.6.4. Amplitude data

MVIC was not collected from the outset due to concerns with its reliability in this age group. Without the use of an MVIC measurement or a footswitch, we were unable to accurately evaluate the level of activity or timing of a muscle group. While we could not make a comparison of muscle activity between muscles or individual participants, it was determined that the surface EMG was potentially useful for limited comparisons as to whether specific muscle groups were active in one intervention compared to another.

The factors we were able to control to ensure high repeatability and consistency of testing included the EMG setup environment. There were no changes to the configuration of the EMG setup. The environment was also constant for the testing as it was completed within a short period of time with the same participant in the same session. However, it was difficult to complete the MVIC in a way that was standardised as per standard protocols including joint positions and adequate rest periods in between trials. The methodology in explaining to a young child to "push as hard as they can" is often difficult. This measurement was difficult in achieving a standardised and consistent measure in this age group. The requirements of a standardised measure with adequate rest in between each test before losing the interest of the child was also determined to be challenging to complete without impacting our primary outcome measure. Therefore, it is difficult to confidently state the validity of our results. While we used children within the study with no known strength deficits, these results are not an accurate representation of their MVIC. The lack of literature in measurement on MVIC in younger children may suggest that amplitude in surface EMG may be difficult to collect (21). In summary, future research using surface EMG and young children may still be possible based on our learnings. We have described the difficulties we encountered during this data collection (Table 14). We have proposed potential solutions for future research that may be tested to overcome these difficulties.

Table 14 Challenges of sEMG in young children

What did we need for it to successfully work in this cohort?	Why it didn't work	What could we do differently?	Challenge
Use of a foot switch, sensors	• Challenges of using foot switch in this age group, validation studies in this age. • Lack of wearable and wireless systems for surface EMG detection that integrate algorithms for the study of gait in natural conditions	Pilot a footswitch in younger children and determine if other studies have methods to overcome any changes to gait in younger children	Data collection and data analysis
No time lock	• While attempted to manually begin EMG with first step of trial, therefore not confident with our results	Use of timed video with EMG	Data analysis
Cross talk of muscles	• Small muscle belly of younger child	Smaller sensors, visual check for cross activity of muscle group.	Data collection
MVIC	• Question if you can get an MVIC on a child this age to obtain these measures. Is MVIC	Further studies to validate MVIC in younger children.	Data collection and data analysis

	feasible in this age group?		

6.7 References Chapter 6

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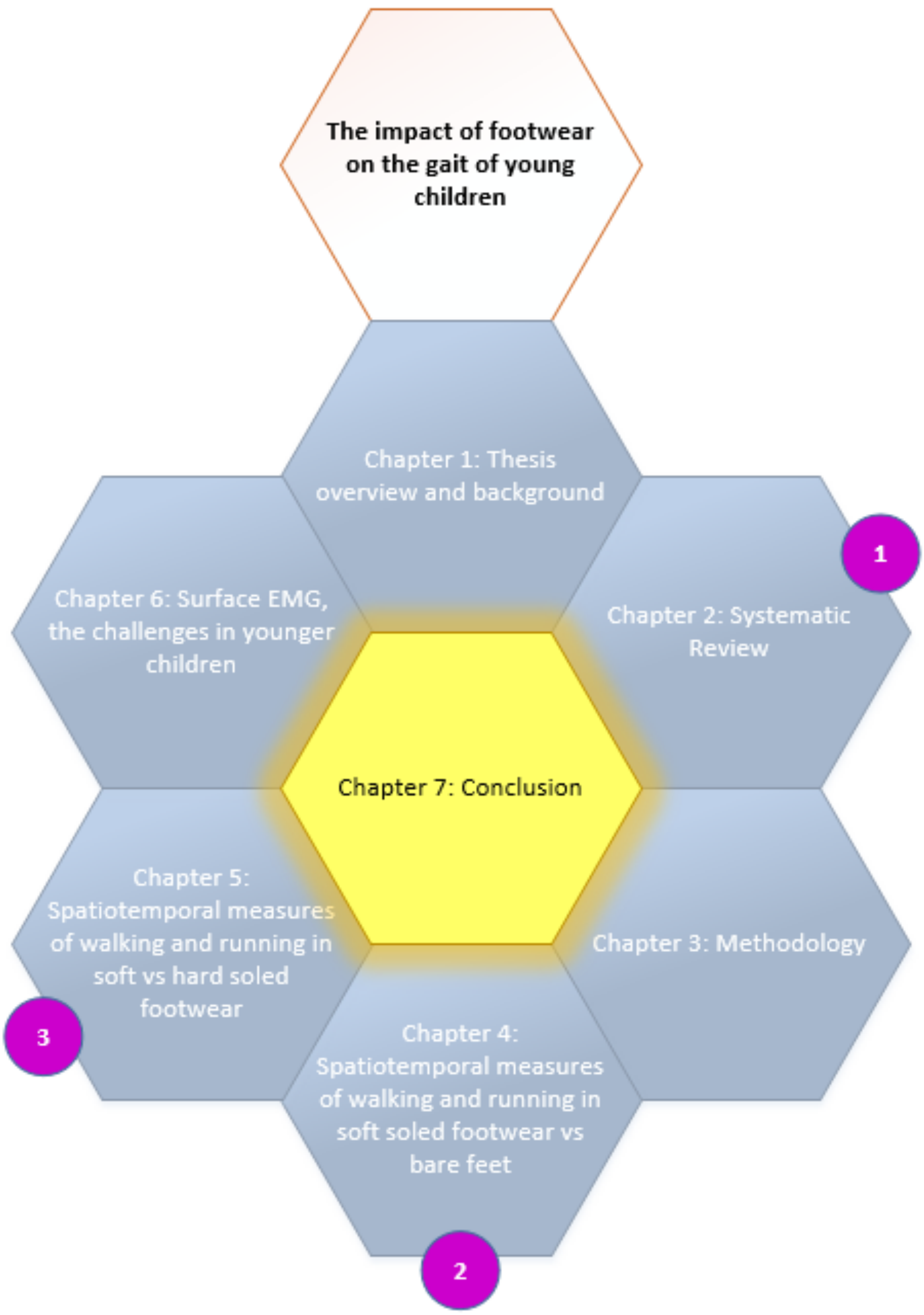
CHAPTER 7- Conclusion

7.1 Preamble



This final chapter of this thesis summarises the findings of the three papers included in this

thesis. The chapter describes the strengths and limitations of each study, how the findings may influence clinical practice and industry, and how best to progress with future research in this area. This thesis has described the results of a systematic review (Chapter 2) into an unknown area of footwear research in younger children. It also presents the methodology and results of further investigations to address the gaps that were identified in the literature (Chapters 3, 4 and 5). This thesis also presents some of the challenges that were encountered in completion of surface EMG in younger children (Chapter 6).

7.2 Summary of Findings

There is an assumption that footwear should have minimal impact on developing foot function or gross motor development and that this should be a fundamental factor when choosing footwear for a young child (1, 2). The limited evidence into how footwear features impact younger children's gait makes it difficult for clinicians to provide evidence-informed recommendations to guide parents on footwear choices. Limited research on the impact of different footwear features also limits manufacturer knowledge on development of footwear to have limited impact on foot development or gait in younger children. This leaves parents, clinicians, and manufacturers to make pragmatic decisions about the importance of footwear features such as the sole of the shoe.

Chapter 2 synthesised the scientific literature describing the impact of footwear features on younger children's gait, with a particular focus on gait differences between footwear sole flexibility compared to barefoot. This review concluded that footwear affected the gait of younger children in a similar way to that of older children with established gait patterns (3). However, it was founded on limited evidence of any effect of particular footwear features such as sole hardness on gait, and no evidence on any changes in muscle activation patterns in footwear with different features.

Chapters 4, 5 and 6 described how we addressed this gap in the literature. We compared young children's spatiotemporal gait measures while walking and running in three common types of soft soled footwear and compared these measures to walking and running bare feet. Chapter 4 provides the summary of how various types of soft-soled footwear impacted gait compared to the barefoot condition, with some differences seen between walking and running trials. These findings challenge any assumptions that soft-soled footwear facilitated a similar gait to barefoot walking and running, although the clinical significance of these differences was unknown.

Chapter 5 provides a summary of the differences in spatiotemporal gait measures of the same cohort of children while walking or running in three different types of footwear with softer or harder soles. There were few differences observed across all of the gait parameters between the different types of footwear or the different types of sole hardness. This is potentially a positive finding for footwear designers and manufacturers, in addition to a cost benefit for parents, as a harder sole appeared to have limited impact gait in young children.

Chapter 6 described the difficulties encountered during data collection and interpretation of surface EMG in this younger cohort of children. The main difficulties encountered included the distractibility of the sensors and the relative size of the sensors to reduce cross signals from nearby muscles groups. In addition, it explored the difficulties of the application of a footswitch and obtaining a maximum voluntary isometric contraction in younger children. These are considerations that need to be taken into account prior to completing surface EMG research in younger children, as these factors have the potential to alter gait and results.

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7.3 Clinical implications

Findings from this research can assist in guiding footwear manufacturers and clinicians related to footwear recommendations for younger children. Parents commonly ask for feature specific or footwear type advice from health professionals. As a result of this research clinicians could cautiously inform parents that soft-soled footwear has minimal impact on walking and running, however they should also be informed that soft-soled footwear is not the same as a child walking in bare feet. Results of this study can assist in the guidance of clinical advice in relation to questions that are commonly asked regarding bare feet and soft soled footwear with up to date evidence.

While these findings cannot be extrapolated to clinical recommendations for transitioning a younger child from soft to harder soled footwear, this research has highlighted the limited impact of sole hardness during walking and running. This may assist footwear manufacturers establish upper limits of sole hardness during the design process to support the robustness of the footwear sole. With increased robustness of the sole, there is the ability to increase the durability without significantly impacting on walking and running. This potentially has a cost benefit for parents as the footwear may last for longer periods of time before replacement footwear is required. It also may allow children with different gait relating to foot deformities or children with a heavier body mass index to be in a shoe that is more durable. These findings also may provide reassurance that footwear with similar features like adjustable dorsal fixation (for example sandals with an ankle strap and forefoot strap or sneakers with Velcro fixation) also have similar and limited impact on walking or running.

This research also may assist footwear companies in the marketing of their footwear to ensure consistencies in health messages being portrayed to the general public. This knowledge may also have a role in moderating how footwear risks and benefits are promoted to parents. This knowledge may also assist health professions to provide accurate information to parents in order for them to make informed choices about their children's footwear.

This thesis also highlights the difficulties encountered during collection of surface EMG data within this cohort of children. This chapter explored the clinical challenges faced with this younger age group, in particular with changing the child's gait pattern as a result of the sensors applied. Clinically it highlights the issues in research around collection of MVIC and the use of foot switches in this younger age group and whether surface EMG was appropriate to be used within this study. As a result of these challenges, data was unable to be adequately analysed to determine if there were any differences observed in muscle activity in the different footwear types and Shore hardness.

7.4 Limitations and future direction

There were a number of limitations we encountered throughout this research which have been highlighted throughout this thesis. The artificial environment of the testing may have impacted on the results of the study. The laboratory environment was new to the participants; therefore, these results may be different to walking and running performance in the playground, particularly as children are used to playing and walking on different surfaces both indoors and outdoors. The GAITRite has also had few reliability studies completed in younger children for running, despite it having a high reliability for walking measurements in children. It was also not feasible to complete a footwear habituation period due to the study design, therefore our results may have been impacted by this.

Our study was limited to spatiotemporal measurements, and there are other important variables that should be considered in future research. There continues to be a lack of research investigating other measures including comfort, muscle activation and force. We did not explore children's footwear preferences or their perceptions on which shoe was more comfortable. It is possible that the difference in sole shore hardness deemed by the study sponsor as outside the range of what they considered as too hard based on parent feedback, was not hard (or rigid) enough to impact gait change.

Additionally, there are no published definitions of footwear features and classifications for young children's footwear. This challenge was encountered during the systematic review while combining data. As future studies are undertaken with different ages, clear definitions of footwear styles and features are needed. Without these classifications other footwear research carried out with younger children, using commercially available footwear, may not be comparable if the footwear is described differently or the features substantially vary.

This research has substantially increased what is known about footwear impact on young children. However, more is still required for health professionals to provide definitive recommendations on the optimal footwear characteristics for younger children, particularly relating to sole hardness. Future research should extend beyond spatiotemporal measures to determine whether shoe and sole flexibility lead to changes in kinetics, kinematics and plantar pressures and overcome the challenges we encountered to explore muscle activation patterns in younger children.

Further research should also investigate how different footwear features, such as heel counters or uppers impacts the gait of young children. This research could include the impact of sole hardness and upper interface on the functional gross motor impact in young children. This would benefit our understanding of any potential therapeutic role footwear may play where there are foot or ankle problems in children. Footwear features also have the potential to impact on a child's comfort and this should be considered in future research of determining upper limits of sole hardness, or lower limits of softness in contrast with durability.

Further research into the impact of gait in younger children with the addition of a footswitch would be useful when looking to complete surface EMG studies in younger children. Children may be habituated or footwear modified in a way to minimise the challenges we encountered with EMG or the challenges posed by the equipment we had within our gait laboratory. In addition, further studies into the reliability of an MVIC in this age group would also be useful for surface EMG studies in the future.

7.5 Concluding remarks

It is important that footwear messages are based on the best available evidence, and that messages are consistent for parents when buying footwear for their children. As a result of this study, we propose that clinicians can cautiously inform parents of the minimal impact of the soft-soled footwear used in this study on walking and running, however it is not the same as a child walking in bare feet. There were few differences seen across all of the spatiotemporal gait parameters between differing sole hardness of footwear in both walking and running. This may have positive benefits for footwear manufacturers and parents. Further research is required in this area into the impact of additional footwear features on functional impact and comfort in young children. Further research is still required into the use of surface EMG in younger children to compare different types of footwear and sole hardness.

7.6 References Chapter 7

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Appendices

Appendix 1 Trial Registration

ANZCTR
Australian New Zealand Clinical Trials Registry

Trial Review
Trial registered on ANZCTR
Registration number ACTRN12617000999336
Ethics application status Approved
Date submitted 5/07/2017
Date registered 11/07/2017
Date last updated 28/07/2017
Type of registration Retrospectively registered

Titles & IDs

Public title Understanding the impact of footwear on young children's gait
Scientific title Understanding the impact of sole hardness and footwear design parameters on young children's gait
Secondary ID [1] None
Universal Trial Number (UTN) Trial acronym
Linked study record

Health condition

Health condition(s) or problem(s) studied:
Paediatric foot development
Condition category **Condition code**
Musculoskeletal Normal musculoskeletal and cartilage development and function

Intervention/exposure

Study type Interventional

Description of intervention(s) / exposure

This study aims to investigate the acute impact of different footwear and footwear features on gait of 2, 3 and 4 year old children. These exposures include boots, sandals, and runners in a soft sole and hard sole to determine the differences between each of the footwear and barefoot as measured on the GAITRite ('Registered Trademark) system. A selection of children will also wear a Trigno EMG Systems for Electromyography (EMG) sensor at the lateral gastrocnemius, biceps femoris and lateral branch of the rectus femoris.

Shoes were selected as commonly wore footwear by children during the different seasons and play. All shoes will have the same features for each participant. The runners have a firm heel counter, and velcro fasteners. The boots are above the ankle, have a zip at the inside and elastic on the outside to assist in fitting and the sandals have velcro strap fixture, enclosed heel and open toe.

Seven conditions will be tested- 1. Barefoot (no footwear) 2. Sandals (Hard sole) 3. Sandals (Soft sole) , 4. Runners (Hard sole), 5. Runners (Soft soles), 6 Boots (Hard sole) and 7. Boot (Soft sole), will be used and the immediate effect on gait will be measured. Each condition consists of three walking trials and three running trials along the GAITRite mat, which is four (4) metres in length. During recording, if the initial or final contact is a partial foot fall, due to the potential for the foot to strike the mat in a partial sensor area, this data will be excluded. All other contacts within the recording, will be recorded for analysis. A one metre space will be provided at each end of the mat to allow the children to accelerate and decelerate as required.
Conditions are as follows: Condition 1: After familiarisation, the child will be asked to remove their footwear and walk along the GAITRite ('Registered Trademark) mat at their preferred pace for 3 passes. Then the child will be asked to run as fast as they can for three passes.
Conditions 2-7: The children will be placed in socks and the footwear of interest while walking along the GAITRite ('Registered Trademark) mat. The child will then repeat the trial running at their select selected fastest.

A randomization procedure by use of a Latin square design will be employed for the seven conditions. Between each of these conditions, there is not anticipated to be a washout period and there will be 5 minutes between each testing period.
I.e.:
Condition 1, Condition 2, Condition 3, Condition 4, Condition 5, Condition 6, Condition 7
Condition 2, Condition 3, Condition 4, Condition 5, Condition 6, Condition 7, Condition 1
Condition 3, Condition 4, Condition 5, Condition 6, Condition 7 Condition 1, Condition 2 etc

The first five children in each age group will wear the Trigno surface EMG during testing.
Intervention code [1] Treatment: Devices
Comparator / control treatment Comparator is the barefoot condition and all other conditions will be compared to the data obained from this condition.
Control group Active

Outcomes

Primary outcome [1] Differences gait velocity assessed by GAITRite system
Timepoint [1] Time of testing during one session only
Primary outcome [2] Differences in gait cadence as measured by the GAITRite system.
Timepoint [2] Time of testing during one session only
Primary outcome [3] Differences in stride length as measured with the GAITRite system
Timepoint [3] Time of testing during one session only
Secondary outcome [1] Differences in muscle activity of the gastrocnemius between conditions as measured with the Trigno.
Timepoint [1] Time of testing during one session only
Secondary outcome [2] Differences in step width between conditions as measured with the GAITRite system
Timepoint [2] Time of testing during one session only
Secondary outcome [3] Differences in the step timing between conditions as measured with the GAITRite system
Timepoint [3] Time of testing during one session only
Secondary outcome [4] Difference intoe/outtoe angle between conditions as measured with the GAITRite system
Timepoint [4] Time of testing during one session only
Secondary outcome [5] Difference in stance percentage between conditions as measured with the GAITRite system
Timepoint [5] Time of testing during one session only
Secondary outcome [6] Difference in swing percentage between conditions as measured with the GAITRite system
Timepoint [6] Time of testing during one session only
Secondary outcome [7] Difference in double support time between conditions as measured with the GAITRite system
Timepoint [7] Time of testing during one session only
Secondary outcome [8] Difference in load/unload time between conditions as measured with the GAITRite system
Timepoint [8] Time of testing during one session only
Secondary outcome [9] Differences in muscle activity of the biceps femoris between conditions as measured with the Trigno.
Timepoint [9] Time of testing during one session only
Secondary outcome [10] Differences in muscle activity of the rectis femoris between conditions as measured with the Trigno.
Timepoint [10] Time of testing during one session only

Eligibility

Key inclusion criteria Community dwelling children with no known gait or lower limb disorders
Minimum age 2 Years
Maximum age 4 Years
Gender Both males and females

Study design

Purpose of the study Treatment
Allocation to intervention Randomised controlled trial
Procedure for enrolling a subject and allocating the treatment (allocation concealment procedures) Allocation is not concealed
Methods used to generate the sequence in which subjects will be randomised (sequence generation) Within subject randomised controlled trial with Latin square allocation for all stimuli conditions

Masking / blinding Open (masking not used)
Who is / are masked / blinded?

Intervention assignment Crossover
Other design features Not applicable
Phase Not Applicable
Type of endpoint(s) Efficacy
Statistical methods / analysis The descriptive statistics will be used to express each variable in means (SD) or frequency (%) for all full foot strikes. Linear regression analyses will be used to determine the difference in outcome measures between the barefoot (condition 1) versus each other condition. The data will be clustered within individual participants and robust variance estimates used to account for the within-subject nature of these data.

Recruitment

Recruitment status Completed

Date of first participant enrolment
Anticipated **Actual** 7/07/2017

Date of last participant enrolment
Anticipated
Actual 20/07/2017

Date of last data collection
Anticipated
Actual 20/07/2017

Sample size
Target 45
Accrual to date **Final** 47

Recruitment in Australia
Recruitment state(s) VIC
Recruitment postcode(s) [1] 3192 - Cheltenham
Recruitment postcode(s) [2] 3198 - Seaford
Recruitment postcode(s) [3] 3199 - Frankston

Funding & Sponsors

Funding source category [1] Commercial sector/Industry
Name [1] Bobux International Pty Ltd
Address [1] PO Box 58-649, Botany, Auckland, New Zealand 2163
Country [1] New Zealand
Primary sponsor type University
Name Monash University
Address McMahon Road,
Frankston, VIC, 3199
Country Australia
Secondary sponsor category [1] None
Name [1]
Address [1]
Country [1]

Ethics approval

Ethics application status Approved
Ethics committee name [1] Monash University
Ethics committee address [1] 21 Chancellors Walk Campus Centre Monash University VIC 3800
Ethics committee country [1] Australia
Date submitted for ethics approval [1] 14/03/2017

Approval date [1] 07/06/2017
Ethics approval number [1] 2017 - 8549

Summary

Brief summary The common footwear advice provided to parents of young children involves seeking out shoes with particular fixtures and features. This advice is historic, and there is little evidence supporting this advice. It is unknown if there are particular features which change children gait. This also comes in the advent on softer and more flexible soles.

This research aims to understand the impact of different features and sole hardness of common footwear on young children's gait compared to walking and running barefoot. That is, comparing sandals, boots and runners in identical styles with different sole hardnesses to barefoot to see if there are any differences.

Trial website
Trial related presentations / publications
Public notes

Contacts
Principal investigator
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Country Australia
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Fax
Email cylie.williams@Monash.edu

No information has been provided regarding IPD availability Summary results
Have study results been published in a peer-reviewed journal?
Other publications

Have study results been made publicly available in another format?

Results – basic reporting Results – plain English summary

Appendix 2: Ethics approval certificate

MONASH University

Monash University Human Research Ethics Committee Approval Certificate

This is to certify that the project below was considered by the Monash University Human Research Ethics Committee. The Committee was satisfied that the proposal meets the requirements of the *National Statement on Ethical Conduct in Human Research* and has granted approval.

Project Number: 8549
Project Title: **Investigating the impact of shoe design on the gait of young children**
Chief Investigator: Dr Cylie Williams
Expiry Date: 21/04/2022

Terms of approval - failure to comply with the terms below is in breach of your approval and the *Australian Code for the Responsible Conduct of Research*.

1. The Chief Investigator is responsible for ensuring that permission letters are obtained, if relevant, before any data collection can occur at the specified organisation.
2. Approval is only valid whilst your hold a position at Monash University.
3. It is responsibility of the Chief Investigator to ensure that all investigators are aware of the terms of approval and to ensure the project is conducted as approved by MUHREC.
4. You should notify MUHREC immediately of any serious or unexpected adverse effects on participants or unforeseen events affecting the ethical acceptability of the project.
5. The Explanatory Statement must be on Monash letterhead and the Monash University complaints clause must include your project number.
6. Amendments to approved projects including changes to personnel must not commence without written approval from MHUREC.
7. Annual Report - continued approval of this project is dependent on the submission of an Annual Report.
8. Final Report - should be provided at the conclusion of the project. MUHREC should be notified if the project is discontinued before the expected completion date.
9. Monitoring - project may be subject to an audit or any other form of monitoring by MUHREC at any time.
10. Retention and storage of data - The Chief Investigator is responsible for the storage and retention of the original data pertaining to the project for a minimum period of five years.

CC: Dr Kelly Bowles, Ms Simone Cranage

List of approved documents:

Document Type	File Name	Date	Version
Consent Form	CONSENT FORM V1.0	29/03/2017	1.0

Supporting Documentation	Participant Randomisation	29/03/2017	1
Supporting Documentation	Flyer-2	02/04/2017	1
Supporting Documentation	GAITRite Data Capture Sheet Bobux	02/04/2017	1
Explanatory Statement	Explanatory statement 11	20/04/2017	1.1

Appendix 3: Information and Consent form

Parent/Guardian Information and Consent

Full Project Title: **Investigating the impact of shoe design on the gait of young children**
Chief Investigator: **Dr Cylie Williams**
Associate Investigators: **Dr Kelly Bowles, Simone Cranage**

1. Introduction

Your child is invited to take part in this research project based on your response to advertising. The aim of this research project is to determine if differences in sole hardness of shoes impact on a child's walking. This Information and Consent Form gives you information about the research project. It explains what is involved to help you decide if you want your child to take part.

Please read this information carefully. Please ask questions about anything that you don't understand or want to know more about. Before deciding whether or not to take part, you might want to talk about it with a relative, friend or your local health worker.

Participation in this research is voluntary. If you don't wish to take part, you don't have to and this will not impact any further assessment or treatment of your child if you do not take part.

If you decide you want to take part in the research project, you will be asked to sign a consent form. By signing it you are stating that you:

- understand what you have read;
- consent to take part in the research project;
- consent to be involved in the procedures described; and
- consent to the use of your personal and health information as described.

You will be given a copy of this Participant Information and Consent Form to keep.

2. What is the purpose of this research project?

There is little research behind the design of young children's shoes, in particular the shoe features and the hardness of the sole or bottom of the shoes.

This study is looking to recruit 45 typically developing children without any medical conditions known to cause gait changes. We will then investigate the impact of three different types of children's shoes. It will also look at any differences between the shoes with different sole hardness' and how these may impact on a child's walking and muscle activity compared to barefoot walking.

Finding out the impact of shoes on children's gait is important for future shoe design and to reduce any negative impacts of shoes on children's walking and running.

3. What does participation in this research project involve?

After you have indicated your interest in your child being part of this study, contact will be made with a member of the research team to organise an initial meeting time for your child to have their foot measured for shoe size. At this time a booking will be made for them to attend Monash University (Peninsula Campus in Frankston) for testing with the GAITRite system.

On the day of testing, your child will be familiarized to the room with the GAITRite mat. This is an electronic walkway that your child will walk and run along. This mat has sensors in it that measure the footsteps of your child and gives us the information like where your child places their foot during walking and running and their speed. Your child will be encouraged to walk across the mat before we start so they are aware of what they need to do. We will help your child stay on the mat, but we may need your help with this also if your child is younger. Your child will be prepared for each condition. Conditions are what we call each time your child wears a different shoe or walk barefoot. Your child will sit or stand between each condition depending on their preference when changing shoes. It expected that this will take less than 45 minutes.

Once your child is familiar with the environment, they will have their height and weight recorded and the testing will begin. Your child will walk across the mat three times at their own selected speed. They will then be encouraged to run as fast as they can across the mat three times. The GAITRite also has a small camera which will record this, it is set low, therefore only the lower limb and foot will be captured and recorded. Your child will not be identifiable.

A small group of children will be randomly selected to have sensors placed on 3 different muscle groups and their muscle activity will be recorded as part of walking and running across the mat. We are selecting five children in each age group. These sensors stick onto the skin like a band-aid. They are about the size of half a matchbox. If your child is selected to have the sensors and they do not like them being stuck onto their skin, the do not have to do this component of the testing.

There is no financial reimbursement made for being part of this research, your and your child's time is voluntary. Your child will be given all of the shoes they have worn during the testing for being a participant in the study.

4. Funding

This research is being funded on contract by Bobux International Ltd. The researchers will be producing a report at the end of the research for Bobux International Ltd on the impact of the shoes on children's gait.

5. What are the possible benefits and risks?

There is no individual benefit from this research other than the contribution to a better understanding of shoes and how they impact on children's gait.

There is limited risk, pain or associated discomfort during any of the testing. If your child is allergic to adhesives, they will not be invited to have the sensors placed on their skin. Prior to adhesion of the sensors the skin is cleaned with a rough wipe to ensure there is no hair or skin oils. This is painless, however in some children it may cause a little redness. It does not break the skin. If there is continued redness we will recommend you seek advice from your doctor.

6. Does my child have to take part in this research project?

Participation in any research project is voluntary. If you decide to allow your child to take part and later change your mind, you are free to withdraw your child from the project prior to attending the appointment at the Monash University.

If you decide to withdraw your child from the study prior to testing, the researcher will not keep any information about your child. Once you have completed the testing, your child's data will be de-identified. If you wish to withdraw your child and have their gait data deleted, you can only do this at the time of testing. After this point, no data can be withdrawn from the study.

Your decision whether to allow your child to take part or not to take part and then withdraw, will not affect your relationship with the researcher or with Monash University.

7. How will I be informed of the final results of this research project?
You will be posted or emailed an outcome statement at the end of the project. It is anticipated that the process and final results will be presented at an allied health conferences and to be published within peer-review journals. You may request a copy of any publications from the researcher at the end of the study. The results may also form a thesis if used by the researcher Simone Cranage in attainment of a research degree.

8. What will happen to information about my child?
Your consent form will be scanned and uploaded separately to your child's gait de-identified gait results, and will be stored within a password protected secure online data server called Lab Archives. Lab Archives are securely maintained by Monash University. These results will be stored for 5 years however they may be published in a data set and therefore remain online indefinitely. Only the researchers named in this project will have access to these consent forms and individual de-identified results.
No identifying information is recorded at the gait assessment and your child's identity will not be disclosed during any of the research. In any publication and/or presentation, information will be provided in such a way that your child and family cannot be identified from the research, except with your specific permission.

10. Is this research project approved?
The ethical aspects of this research project have been approved by the Human Research Ethics Committee of Monash University.
This project will be carried out according to the *National Statement on Ethical Conduct in Human Research (2007)* produced by the National Health and Medical Research Council of Australia. This statement has been developed to protect the interests of people who agree to participate in human research studies.

12. Who can I contact?
The person you may need to contact will depend on the nature of your query. Therefore, please note the following:
For further information or appointments:
If you want any further information concerning this project or if you have any problems which may be related to your involvement in the project (for example, feelings of distress), you can contact Cylie Williams on **97842678** or Kelly-Ann Bowles on **99044176**
Complaints
Should you have any concerns or complaints about the conduct of the project, you are welcome to contact the Executive Officer, Monash University Human Research Ethics (MUHREC):
Executive Officer
Monash University Human Research Ethics Committee (MUHREC)
Room 111, Chancellery Building E,
24 Sports Walk, Clayton Campus
Research Office
Monash University VIC 3800
Tel: +61 3 9905 2052 Email: muhrec@monash.edu Fax: +61 3 9905 3831

MONASH University
Medicine, Nursing and Health Sciences

CONSENT FORM

Project: **Investigating the impact of shoe design on the gait of young children**

Researchers: *Dr Cylie Williams Dr Kelly-Ann Bowles, Simone Cranage*

I am the parent/guardian and my child has been asked to take part in a study by Monash University. I have read and understood the explanatory statement and I agree for my child to participate in this project.

I understand the purposes, procedures and risks of this research project. I have had an opportunity to ask questions and I am satisfied with the answers I have received. I understand I can also give my email to gain a copy of the final results and it will only be used for this purpose.

I consent to the following:	***Yes***	***No***
(Child name)____ participating in the study	☐	☐

By signing your name on this page, you are confirming your child has no developmental delays or medical concerns that cause changes in gait and agree for your child to take part in this research study.
Signature____ Date_______

Printed name ____

I wish to have a copy of the study report to emailed to me: No ☐ Yes ☐
Email:____

I have explained this study and answered questions of the child and parent. I informed the child that they could stop being in the study and can ask questions at any time. The parent/guardian has consented and the child assented to participate.
Research team member signature____________________________Date________
Printed Name ____

Appendix 4: Website footwear sponsor

https://www.bobux.com.au/toddler-preschooler