The impact of footwear choice on foot biomechanics in young adults with considerations to the potential risk of developing foot pathology

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Contents

Publications: (Appendices 1-14)

1) Branthwaite, H.R., Chockalingam, N. (2009). **What influences someone when purchasing new trainers?** *Footwear Science*, 1(2), 71 – 72.

2) Branthwaite, H.R., Chockalingam, N. (2009). **The role of footwear in rehabilitation: A Review.** *The Internet Journal of Rehabilitation*, 1 (1). https://ispub.com/IJRE/1/1/13487 [February 2015]

3) Branthwaite, H.R. (2010). Footwear: The Forgotten Treatment. **Britpods**, Coventry, UK. June.

4) Branthwaite, H.R., Naemi, R., Chockalingam, N. (2010). The effect of negative heel profile shoes on triceps surae**. International Foot and Ankle Biomechanics- i FAB** Seattle, USA. September.

5) Branthwaite, H.R., Chockalingam, N., Healy, A. (2012). Footwear - the forgotten treatment - Clinical role of footwear. Goonetilleke, R.S. ***The Science of Footwear*** Chapter 16: p 341-352. CRC Press.

6) Branthwaite, H.R., Pandyan, A., Chockalingam, N. (2012). **Function of the triceps surae muscle group in low and high arched feet: An exploratory study.** *The Foot,* 22(2), 56-59.

7) Branthwaite, H.R., Chockalingam, N, Jones, M., Grogan, S. (2012). **Footwear choices made by young women and their potential impact on foot health.** *Journal of Health Psychology,* 27(11), 1-10.

8) Johnson, S., Branthwaite, H.R., Chockalingam, N. (2012). **The effect of three different toe props on plantar pressure and patient comfort** *Journal of Foot and Ankle Research*. 5:22 doi:10.1186/1757-1146-5-22. http://www.jfootankleres.com/content/5/1/22 [February 2015]

9) Branthwaite, H.R., Chockalingam, N., Pandyan, A., Khatri, G., (2012). **Evaluation of lower limb electromyographic activity when using unstable shoes for the first time: A pilot quasi control trial.** *Prosthetics and Orthotic International*, 37(4), 275-281.

10) Branthwaite, H.R., Chocklingam, N., Greenhalgh, A. (2013). **The effect of shoe toe box shape on forefoot interdigital and plantar pressures.** *Journal of Foot and Ankle Research*. 6:28 doi: 10.1186/1757-1146-6-28. http://www.jfootankleres.com/content/6/1/28 [February 2015]

11) Branthwaite, H.R., Chocklingam, N., Greenhalgh, A. (2013). The Effect of Footwear Design on Interdigital and Plantar Pressures. **Staffordshire University Clinical Biomechanics**, Stoke on Trent, UK. April.

12) Branthwaite, H.R., Chatzistergos, P., Chockalingam, N. (2013). The relationship between stiffness and comfort in casual ballet pump shoes. - A pilot study.

Footwear Biomechanics Group Natal, Brazil. August. *Footwear Science*, 5(sup1), S23-S24.

13) Branthwaite H,R. (2013). The reported effects and clinical uses of wearing an unstable shoe. **Society of Chiropodists and Podiatrist** Liverpool, UK. November.

14) Branthwaite, H.R., Chockalingam, N., Greenhalgh, A., Chatzistergos, P. (2014). **The impact of different footwear characteristics on centre of pressure progression and perceived comfort.** *The Foot,* 24(3),116-122.

15) Ethical Approval.

16) Co-author contribution statements.

Format of Thesis

The origins of the thesis are based on 20 years clinical experience working with patients that have suffered from footwear related foot pathologies. The collection of research outputs explore the role footwear plays as a precursor to foot pathology in healthy individuals as well as its role in treatment. The selection of published outputs are categorised into three research themes that focus on young healthy people who have not yet developed footwear related pathologies. The defined themes are; the choices made when buying footwear (Chapter 2), the impact of footwear on comfort and mechanics (Chapter 3) and the effect of unstable shoes on function (Chapter 4).

This area of footwear research has not been previously explored and this thesis has been constructed to demonstrate a coherent and original contribution of knowledge around the subject of everyday footwear.

The selection of publications described have co-authorship. Where Helen Branthwaite is stated as the lead author, she has instigated, designed, collected data, analysed and prepared the manuscripts. Papers submitted where Helen Branthwaite is not the lead author have been conducted by collaborators and Helen Branthwaite has contributed significantly to the work and then solely led the publication. Statements of author contribution can be found in the Appendix 16 of this thesis.

Acknowledgements

Throughout the time preparing, delivering this research and final publication of all the mentioned manuscripts included in this thesis there have been many colleagues involved in completion of the work. Specifically I would like to express thanks to all co-authors who shared their own expertise and supported the work I conducted - all their time and effort is greatly appreciated. I would like to thank and acknowledge the support given to me by the CSHER (Centre for Sport Health Exercise Research), especially for awarding my research with a small internal staff grant that enabled me to purchase all the shoes that were tested. I would also like to thank Professor Nachiappan Chockalingam for mentoring all this work and generally encouraging me to complete this award.

Individuals who are not mentioned in the published text who have also helped in completing this work include Mark Young (Health Technician), Dave Dunning (Fellow Podiatrist), Barbara Brown (Administration Support), Dr Gill Parkinson (inspiration and external support) and my family and friends.

List of Figures and Tables

Abstract

Foot pain and pathology can be disabling leading to more complex orthopaedic complaints over time. Footwear is often attributed as a significant factor in the development and persistence of foot pain, yet little is known about the impact everyday footwear choice has on the development of these pathologies and foot biomechanics. The aim of this collection of work is to assess the impact footwear choice has on foot biomechanics.

A mixed methods approach has been employed across various publications to investigate the following; choices made when purchasing footwear, the impact footwear structure and styling has on foot mechanics and comfort and the effect of unstable shoes on muscle function. The publications employed literature reviews, qualitative questionnaires, repeated measures and quasi-experimental designs to address the research questions.

There is a paucity of research regarding the effects that everyday footwear have on the feet of healthy individuals. A flat ballet pump was found to be the primary shoe of choice for young females with the colour of trainers being selected by sport science students. Altered physical characteristics of the shoe caused elevated dorsal and plantar foot pressure, impaired comfort and altered function. Fashionable exercise shoes were shown to demonstrate a varied effect on muscle activity.

The availability of suitably fashionable and functional footwear appears to be severely limited leading to consumers purchasing inappropriate and ill-fitting footwear that may contribute to foot pathology. An extensive review of design, properties and manufacture with specific consideration to pathology in the footwear industry is recommended to improve footwear choice.

The publications presented add new knowledge when evaluating consumer choice of footwear and the potentially adverse impact popular female fashion shoes have on foot biomechanics. The results also contribute to a wider understanding of the impact everyday footwear has on foot pathology and help in the application of footwear related treatment and rehabilitation plans.

Chapter 1

Introduction

1.1 Footwear over time

The use of footwear over time has changed from a shoe being used as a layer of protection and warmth in neotholic man to becoming a fashion accessory and part of a person's identity and persona in modern day (McDowell, 1984). These strong influences on style and image have resulted in most shoes being designed for the fashion industry rather than to support foot function. Evolution of footwear structure and manufacture over time is thought to have played an important role in the observed foot pathologies seen commonly today. Shape, fit and styling of the shoe is believed to be the most likely cause, with foot pain in the elderly population associated with ill-fitting narrow shoes (Burns et al., 2002). It is however unclear at what stage in a person's life a disparity between foot shape and shoe shape occurs.

1.2 Ill-fitting footwear

Literature supports the view that there appears to be a positive correlation between painful foot pathologies in the elderly and ill-fitting footwear (Paiva de Castro et al., 2010, Mickle et al., 2011). However, this view does not appear to influence preventative clinical advice to change footwear habits at an earlier age as prophylactic footwear advice is either very slow in progression or non-existent. This results in a continuous stream of footwear related pathologies as people age.

Foot pain contributes to 20% of hospital orthopaedic referrals and surgical procedures (Hewitt et al., 2011) with a larger proportion (24%-41%) of the population suffering from foot pathology (Riskowski et al., 2011, Garrow et al., 2004). Most foot pathologies are complex in nature with varying aetiologies. Pathologies of the foot have been associated with many different causes including obesity, prolonged standing, bone shape, trauma, congenital defects, foot mechanics, foot posture, inappropriate fitting footwear and reduced range of motion within the foot (Chuckpaiwong et al., 2009). The combination of intrinsic and extrinsic aetiologies make it difficult to isolate one clear cause of a foot problem. Each of these aetiologies will manifest in a different way for each individual. Factors such as genetic profile, hypermobility in the joint and muscle imbalance have been attributed to common complaints like hallux adducto valgus. However, the exact cause is still disputed. (Menz and Lord 1999, Mickle et al.,2010) Previous studies highlight that, ill-fitting footwear is felt to be a significant factor in the development of painful foot pathologies including; hallux adducto varus, metatarsalgia pain, foot ulceration, plantar fasciitis and generic foot pain (Burns et al., 2002, Speed et al., 2003, Paiva de Castro et al., 2010). Footwear has also been associated with acute and chronic ankle injury, related to impaired proprioception (Kerr et al., 2009).

Females are 40% more likely to report significant foot pain than men (Hill et al., 2008). The fit and style of the shoe related to the dimensions of the wearer's foot are highlighted as being the most significant in the development of foot pain in females (Au and Goonetilleke, 2007). The difference in incidence between gender is not fully established yet fashion and styling of female shoes is often thought to be most significant. Therefore, frequent use of an irregular ill-fitting styled shoe that compresses the foot into a smaller dimension in younger females could significantly contribute to the development of related foot pathologies observed in older females. Education of footwear choices made earlier in life could alter the incidence of disabling pathologies seen in elderly patients.

1.3 Fashion versus Function

Fashionable footwear commenced as far back as the Roman era with reports that Julius Caesar wore boots with golden embossed soles when out parading on ceremony. The styles and trends of shoes have evolved over time but have also shown a cyclical and repetitive nature regarding what is considered fashionable. Poulaines, originally thought to be a symbol of wealth and sexuality, were worn as far back as 1300 and have been resurrected frequently throughout the ages appearing in the 1960s as the well-known Winkle Picker (McDowell, 1989). This pointed styling has often been thought to be the reason why shod communities have a higher prevalence of hallux adducto varus compared to unshod communities as the foot is persistently squashed into a smaller area (Ferrari et al., 2004). Yet, the forgotten purpose of the shoe as a protective layer between the ground and the foot is demonstrated, with 44% of women being prepared to wear painful shoes to look fashionable (Phelan, 2002). However, it is not known if all footwear choices made by women are based solely on fashion grounds or if function, comfort, purpose and cost are equally considered when buying shoes. Similarly, it is also not known what mechanical effect popular everyday footwear choices have on foot function.

1.4 Research Problem

Current published research on the effects of footwear on the foot focus on:

- tertiary care in the elderly
- orthopaedic footwear for gross foot pathology, rheumatology and diabetes
- athletic running shoes' design and effect on injury
- high heels and forefoot plantar pressure

A review of the relevant literature indicates that there is limited knowledge and understanding about the effects everyday shoes have on healthy young people's feet. The influence everyday shoes have on developing foot pathologies is unclear, and education of footwear choices as well as the impact on foot health for the general population are non-existent. It is also not known what significance footwear structure has on foot mechanics before pathology arises. The scope of this thesis therefore is to:

1) Consider what factors influence footwear choices when buying shoes.
2) Investigate the effect of everyday footwear on foot mechanics, specifically pressure and comfort.
3) Explore current footwear trends and investigate what impact wearing an unstable exercise shoe has on muscle activity.

This work provides an initial foundation to developing an understanding of the role footwear plays in foot pathology. However, this collection of work does not extend to clinical trials investigating changing footwear as part of a foot health treatment plan. Although the impact of footwear on pathology is considered in the discussions associated with this thesis, direct research of footwear on clinical presentations is beyond the scope.

1.5 Research Question

General (RQG)

What impact does footwear choice have on foot biomechanics in younger generations living in the UK?

Additional to this overall question individual research questions were explored by the presented outputs which set out to investigate the following specific areas of research interest;

Specific Research Question 1 (SRQ1)

What choices are made when purchasing shoes?

Specific Research Question 2 (SRQ2)

What are the effects of the most popular everyday shoes on:

- dorsal pressure
- plantar pressure
- centre of pressure progression
- comfort

Specific Research Question 3 (SRQ3)

What are the immediate effects on muscle activity in the lower limb when wearing an unstable shoe?

Consideration was also given to examining the use of shoes to change foot function and also to examine how a shoe can be used as part of a treatment plan within the context of rehabilitation.

1.6. Specific Aims and Objectives

1. To investigate the choices made when purchasing everyday footwear and what factors influence these decisions.
   (Publications 1, 3 & 7)
2. To investigate the different structural and styling characteristics of footwear chosen for everyday use and the relationship to the consideration of comfort, dorsal toe pressure, plantar toe pressure and centre of pressure progression.
   (Publications 2,5,8,10-12 &14)
3. To look at how modern footwear concepts and styling alter function and investigate if exercise shoes can be used as an intervention in the presence of patient pathology.
   (Publications 2, 4, 5, 6, 9 & 13)

To address the overall research question (RQG) and specific aims and objectives a mixed methodological approach was adopted. Qualitative designs were utilised to gain opinion about footwear choices and comfort (SRQ1). Quantitative methods were chosen to gather data regarding EMG muscle activity, plantar pressure variables and centre of pressure progression as well as shoe physical characteristics (SRQ2/SRQ3). Utilising a diverse methodical approach enabled both the mechanical and image components to be researched.

Chapter 2

The Choices Made When Purchasing Shoes

2.1 Introduction

Footwear choice can play a significant role in the development of foot pathology where using an ill-fitting shoe can increase pain, worsening quality of life and function (Barton et al., 2009, Paiva de Castro et al., 2010). In order to evaluate the previous research completed on everyday footwear and its potential uses, two literature reviews were conducted (*Publications 2 & 5*). The aim of the reviews was to look at the uses of footwear in clinical management and also to understand developments in technology, for footwear in the athletic community. A secondary aim of conducting the reviews was to develop specific research questions in the area of every day footwear by recognising previous work on the impact on foot health from wearing various types of footwear.

Prescribed footwear, with specific modifications, are often used in the management of patients who have developed significant joint deformities. These deformities can be related to an increase in plantar foot pressures, altered gait patterns including reduced stability and balance. Figure 1 depicts images of footwear often prescribed for such conditions. The materials used in the manufacture of the upper and sole characteristics are tailored to the patients' needs. The shoes prescribed are often deemed as unsightly and are not worn frequently by the patients they were intended for (Williams et al., 2007), supporting the notion that the role footwear plays in self-identity and image is important through all patient groups

Figure 1 – Bespoke Orthopaedic footwear used for specific complaints with altered material upper and sole construction

Athletic footwear is frequently researched to explore the impact on injury, however, application of specific shoe designs in the management of everyday foot pain and pathology are forgotten or overlooked. From the literature review (*Publication 5*), specific features in athletic shoe structure were highlighted, detailing the key features of design and the impact they have on injury. (Table 1)

Table 1: Specific running shoe characteristics with research results which can be applied to patient management plans

Design Feature		**Application**
Shoe Weight		Oxygen consumption improved 1% for every 100g lost in weight (Morgan et al.,1989).
Heel Counter		Higher heel collar related to improved stability and proprioception (Menz and Lord 1999).
Sole and Midsole	Thickness	Thinner soles improve stability and balance (Perry et al., 2007).
	Sole Design	Severe grip on sole increases risk of falling (Menz and Morris, 2004).
	Inserts	Can be tailored to individual needs and requirements with additions to support or alter foot function (Payne et al., 2005).
	Shock	Alterations in plantar pressure and altered muscle activity (Clinghan et al., 2008, Nigg 2001).
	Material	Deformation of materials over time can influence original properties. Shoes should have a recovery period and constant use avoided (Taunton et al., 2003).
Comfort and Cushioning		Assessment of footwear fitting (Mündermann et al., 2003).
Neutral Shoes		Reduced anterior muscle group activity (O'Connor and Hamill 2004).

Although there is a plethora of work (Table 1) that demonstrates what effect key design features in athletics shoes have on physical and mechanical function there is no understanding of whether people are influenced by these features when purchasing the shoe. This lack of understanding generated SRQ1 focusing on what factors influenced sport shoe choice.

Through conducting these reviews, the conclusions produced a research synthesis that unequivocally demonstrated a restricted understanding of what choices people made when purchasing footwear and whether fashion or function of the shoe impacted decisions (SRQ1). The reviews also demonstrated a lack of existing quantitative research in the public domain investigating the direct impact that everyday footwear has on feet in younger generations. The majority of previous work published was conducted primarily on elderly or athletic populations. (Nigg 2001, Taunton et al., 2003, O'Conner and Hamil 2004, Menz and Morris 2005, Mickle et al., 2010). Therefore, the aim of the two publications in Table 2 was to investigate the factors that influenced choice when purchasing every day and athletic shoes in a young population.

Table 2: Synopsis of Publications 1 and 7

Publication	**Appendix**	**Overview**	**Contribution to Knowledge**
Branthwaite, H.R., Chockalingam, N. (2009). **What influences someone when purchasing new trainers?** *Footwear Science*, 1(2), 71 – 72.	**1**	Questionnaire based study that investigated the choices made by Sport and Exercise Students when buying new trainers. The colour of the shoe was the most influential factor followed by brand with Adidas being worn by 50% of the students. Students wore the shoes for everyday activities more than specifically for a sport.	Sport and Exercise students are more influenced by a red trainer styling over the functional properties that are marketed as features by trainer companies. Style and image play and important role in footwear choice
Branthwaite, H.R., Chockalingam, N, Jones, M., Grogan, S. (2012). **Footwear**	**7**	Questionnaire study building on the work completed in	Foot measurements and shape were not considered

choices made by young women and their potential impact on foot health. *Journal of Health Psychology,* 27(11), 1-10.		Publication 1, the sample this time however was sixth form female students. The choices they made for footwear were based around activity and comfort and most students wore a flat ballet pump for everyday use with different styling	when buying shoes at all, the main factors that influenced subjects was the comfort of the shoe. Most people felt happy when wearing their chosen shoe indicating the significant role footwear has in well- being and image.

2.2 Method

To develop an understanding of the style and design of shoe purchase, a multi-faceted questionnaire was created to capture the subjects' thoughts regarding footwear image, design, function and sizing (SRQ1 & 1.6 Aim 1). The structure of the questionnaire was initially tested in *Publication 1,* where sports science students were specifically targeted to develop an understanding of sport shoe choice. The questionnaire explored what factors of sport shoe manufacture and marketing influenced the choice when buying a new sports shoe. The questionnaire also investigated how subjects felt about the shoes they wore. *Publication 7* then built on this questionnaire design with developments including an indication of the style of footwear chosen, purpose of shoes purchased and an in-depth investigation into the emotions associated with wearing chosen footwear. The study also aimed to collect data about footwear fitting and foot size and sampled subjects from a sixth form college to understand what shoe choices were made for everyday footwear by young females.

Delivery of the questionnaire via university lectures and school assembly assured a high response rate of 95% and 94.8%. Although this is to be expected with questionnaire return, 70-90% can be accepted as a suitable return to avoid bias (Robson, 2002). The completed questionnaires demonstrated interesting results with vital and formative data on how younger people view shoes and choose them in accordance with what they are doing and what they wish to look like. Because the questionnaire design allowed for expression of personal opinions this method of data collection allowed informal and individual thoughts to be expressed thus enriching the data with specific comments and responses regarding footwear choice. Previous work has not looked at what shoes people choose and therefore footwear advice to get people to change habits has been limited. This published work assists a clinicians understanding of the influences style and image have on footwear choice and how these factors should be considered when promoting footwear changes amongst patients.

From the outcomes of these 2 publications further work has already commenced to advance this questionnaire with a group of people who suffer from foot pain to assess if their choices are different. Developing a focus group prior to data collection and running a pilot study has improved the structure and content of the questionnaire and data collection. This has been implemented in further work developed by our research group.[1]

2.3 Results and Discussion

2.3.1 Sports Shoe Choices

Initially it was thought that sports and exercise students would purchase the trainers they wore based on the technology promoted by the sports company. However, the emphasis for choice placed by respondents was heavily weighted towards the colour and brand of the shoe over the function and performance features marketed by the manufacturer. Findings from this questionnaire were surprising and strengthened the existing research knowledge, demonstrating the need for more detailed inquiry. The findings also drove further thoughts as to why people choose the shoes they wear and helped focus the overall aim of this thesis specifically when considering what influences people when purchasing everyday shoes. Furthermore, the results from the sports science students purchasing athletic shoes were based on image only and ignored the functional element of the shoe. This provoked thought as to whether the popular and fashionable unstable shoes were an image item or actually altered foot function (Chapter 4).

[1] - M.Mcritchie. *Footwear choices in a clinical population* MSC Dissertation expected completion 2015

- Branthwaite et al., *Footwear Choices for Painful Feet – Focus Group* OA Musculoskeletal Medicine in Press 2015

2.3.2 Everyday shoe choices

The main results indicated that young females choose their shoes based on the activity they are doing and choices are strongly related to the comfort and feel of the shoe. The most popular shoe of choice for everyday wear was the flat ballet pump shoe, with a heeled shoe being worn for occasions and an UGG® boot for warmth. Footwear makes this group feel happy and cheerful and has a positive impact on self-esteem; therefore footwear plays an important role in image and positivity for young females.

Footwear fit and measurement, as well as function of the shoe, was not considered as important when buying shoes. None of the subjects had a foot measurement prior to buying shoes and would often move around sizes to make an acceptable fit. Measuring feet of children is deemed as a critical job of a parent and the type of shoe worn is portrayed as essential for a good foot structure (Davies et al., 2014). It is unknown at what point society stop measuring children's feet, the mean age of this sample was 17 years and nobody considered foot measurement when purchasing new shoes. The lack of attention to sizing could in fact lead to the wrong size of shoe being worn for a large proportion of someone's life and could therefore be the main source of pain in older adults. It is well documented that elderly people wear a shoe that is too small for them (Frey et al., 1993, Burns et al., 2002). This could have resulted from a life time of not measuring the foot and assuming a size that was last measured in childhood. The results from this questionnaire also suggest that when buying a shoe little thought is given to the implications of wearing a shoe that is too tight, that the shoe may alter gait pattern and cause foot pathology. The choice of shoe seems only to be led by fashion and little individuality existed amongst the group with the majority of subjects choosing the same footwear styles regardless of foot size, shape and fit. This culture of image and fashion seen in younger generations who 'follow the crowd' may also play a significant role in the development of footwear-related pain in the elderly, as foot shape and anthropometric data remain high in variance amongst populations, yet the availability of varying footwear shape and style for people to buy remains constant.

2.3.3 Critique

Collection of data solely by questionnaire may have limited the breadth of discussion and data collected from these studies. The structure of open and closed questions may have prohibited the expression of emotion regarding footwear choice and in-depth descriptions could have been lost in the design of the questions used. Developing further methods of data collection with interviews and focus groups could have expanded opinions and discussions relating to what influences footwear purchases. However, the results have generated some baseline data to expand and advance research into footwear choices, because the role personal preference plays on the development of foot pathology is still thought to be significant. A recent publication on footwear choice in the elderly showed that aesthetics and comfort were still the most important factors when looking for new shoes (Davis et al., 2013). The importance of body image, even in the later years of life, should be emphasised to designers when they are making comfort, therapeutic and functional shoes for the general population to buy on the high street.

2.3.4 Contribution to knowledge

Footwear choices in younger generations and the role shoes play in image and emotion have not been previously investigated. The results of this work are original and provide crucial information about the potential role shoes have on the development of pathology later in life based on buying habits during formative years. Many studies regarding footwear investigate the elderly and how shoes interfere with pressure, balance or create pain (Menz and Morris, 2005, Mickle and Steele, 2011, Pavia de Castro et al., 2010. Lane et al., 2014). Developing an understanding of what choices younger generation's make prior to pathology arising will assist in further analysis on shoes.

From exploring the uses of footwear and understanding the choices made when buying athletic shoes a university certificate course for shoe shop assistants/sports retailers was developed and validated. This course is aimed at enabling advice to be given to consumers about footwear and how shoes can be used to improve comfort and performance.

2.4 Conclusion

Designers of high street shoes are starting to take note of consumers with footwear-related pain with new developments in comfortable fashion shoes being produced. An overall acceptance in younger generations that wearing ill-fitting footwear during their youth may have an impact on foot-health complaints as they age has yet to be established. Image and fashion persistently dominate the choices made when purchasing new shoes and should be considered when clinical footwear advice is distributed. Athletic footwear designs are constantly being altered with current trends and colours, however it appears that the functional element of footwear design are mainly ignored by younger student consumers.

Chapter 3

The impact of footwear on comfort and foot mechanics

3.1 Introduction

After establishing which style of footwear is the most popular everyday choice for young females from *Publication 7*, further investigations were designed to evaluate if the varying characteristics of the shoe would alter digital pressure, motion and comfort. (SRQ2 Aim 1.6.2).

Altering the styling of a shoe can provide symptom relief from a number of common hyperkeratotic skin complaints and musculoskeletal disorders. *Publication 3* was delivered as a key note lecture at a national podiatry conference to highlight the uses of footwear in the management of common foot complaints. The main ethos of this lecture was to highlight that footwear styling is frequently overlooked in treatment plans and shoes can be a useful tool to alter foot function. For instance, there are numerous reports as to the ill effects of wearing high heels, (Lee et al., 2001, Cowley et al., 2009) yet, using a heeled shoe to alleviate strain on the Achilles tendon for a short period of time can be beneficial. Similarly, the impact and associated pain of wearing ill-fitting footwear for a short period of time is thought to be reversible (Odedra et al.,2010). However, continual use of ill-fitting footwear over a human's life time could be the reason why permanent damage and pathologies are seen in elderly patients reporting to be wearing footwear that causes pain (Pavia de Castro et al., 2010). For example, a tight shoe worn for 2-3 hours may create a small blister but if worn persistently for 20 years may contribute to a significant joint pathology.

The publications described below recruited young healthy females with no foot pathology to investigate what effect different styled ballet pump shoes had on pathology related outcome measures and comfort.

Table 3: Synopsis of Publications 8, 10-12 and 14

Publication	Appendix	Overview	Contribution to Knowledge
Johnson, S., Branthwaite, H.R., Chockalingam, N. (2012). **The effect of three different toe props on plantar pressure and patient comfort** *Journal of Foot and Ankle Research*,	**8**	This study utilised the walkinsense pressure sensor technology to determine if using toe	This paper developed and validated a protocol for application of single sensor digital pressure sensors.

5:22 doi:10.1186/1757-1146-5-22. http://www.jfootankleres.com/content/5/1/22 [February 2015]		props altered apical pressure on pathological digits. The results showed that a silicone prop was most effective at reducing the pressure	This protocol was used to inform further work but was also the first method to specifically record digital pressure with a single pressure sensor
Branthwaite, H.R., Chocklingam, N., Greenhalgh, A. (2013). **The effect of shoe toe box shape on forefoot interdigital and plantar pressures.** *Journal of Foot and Ankle Research*. 6:28 doi: 10.1186/1757-1146-6-28. http://www.jfootankleres.com/content/6/1/28 [February 2015] Branthwaite, H.R., Chocklingam, N., Greenhalgh, A. (2013). The Effect of Footwear Design on Interdigital and Plantar Pressures. **Staffordshire University Clinical Biomechanics**, Stoke on Trent, UK. April.	**10** **11**	Ballet pump slip on shoes with different toe box styling were chosen to represent everyday footwear worn by younger individuals. Measurements of plantar and interdigital pressure were compared between footwear styles to assess the impact altered toe box volume has on these outcomes which are known to contribute to painful pathology in the elderly.	Toe box shape does influence pressure readings with a round toe box exerting the least amount of pressure on the medial side of the hallux and a pointed shoe creating the least pressure on the lateral toes. Footwear shape and styling at the toe box would be better suited for the normal non pathological foot with a round medial border and a gradual pointed lateral border.
Branthwaite, H.R., Chockalingam, N., Greenhalgh, A., Chatzistergos, P. (2014). **The impact of different footwear characteristics on centre of pressure progression and perceived comfort.** *The Foot,* 24(3),116-122. Branthwaite, H.R., Chatzistergos, P., Chockalingam, N. (2013). The relationship between stiffness and comfort in casual ballet pump shoes. - A pilot study. **Footwear Biomechanics Group** Natal,	**14** **12**	Characteristics of the ballet pump shoe were evaluated and measured and correlated to the comfort score for each shoe. Increased bending stiffness at the forefoot was more comfortable than a stiffer soled shoe. Centre of pressure progression angle was centralised to the	Bending stiffness is normally assessed by subjective clinical measures, development of a tool and protocol to evaluate bending stiffness enabled a quantitative value to be produced. This was correlated to comfort score of the foot and this research highlighted that in a normal non pathological foot a more flexible sole unit is more comfortable than a stiffer

Brazil. August. *Footwear Science*, 5(sup1), S23-S24.		longitudinal axis of the foot whilst wearing footwear.	sole. Footwear also improves forward progression of the body and stabilises the centre of pressure. Therefore this work has indicated that footwear improves walking stability and is better than being barefoot.

3.2 Method

Pressure analysis was chosen over other mechanical measures of function to directly relate results to complex footwear related pathologies seen in elderly populations where pressure is deemed as contributory to pain (Paiva de Castro et al., 2010). The choice to measure pressure over kinematic analysis was also dictated as an outcome by the minimal style of shoe (Figure 2) leading to the additional difficulties associated with suitable marker placement. Known issues with marker placements, which can cause structural damage to shoes, impact on the reliability and validity of data collection and analysis. Marker placement and segment analysis development for 3D foot kinematics are ongoing research areas whose methodology is not yet suitably established (Pratt et al., 2012).

Figure 2 – Minimal structure of the flat ballet pump shoes with altered forefoot toe box shape

Variations between kinematic foot and ankle models still exist with lack of consensus to which model is most reliable in capturing valid and accurate information (Bishop et al., 2013). For these reasons the choice of assessing the impact footwear had on 3D kinematics was excluded and the focus for foot function was directed towards pressure data.

3.2.1 Dorsal Pressure

Dorsal digital pressure is rarely reported on, because the core interest for researchers is often plantar foot pressure. However, the dorsal aspect of the digit is often irritated by footwear due to the styling and shape of the shoe at the toe box. Therefore to assess the impact of different toe box shapes pressure sensors were individually placed on anatomical areas identified as problematic locations for patients with superficial blister and corn formation (Figure 3). These chosen landmarks were specifically selected to record the impact footwear styling at the toe box has on forefoot compression. The protocol for sensor placement was initially tested in *Publication 8* where the sensors were used to record apical pressure. The outcome measures derived from this data included peak pressure, time to peak pressure, contact time and the pressure time integral. These outcomes were chosen as not only the amount of pressure applied to soft tissue but the length of time the pressure is present for is felt to be central to the formation of callus and soft tissue pathology (Lavery et al., 2003) This method was adapted for the method used in *Publication 10 & 11* by moving the sensors to the borders of the interphalangeal joints reflecting irritation from footwear on the foot.

The sensors used are innovative and allow for accurate placement in a focal area. They are 1cm in diameter and less than a millimetre thick, they were easy to apply and were secured in place with adhesive. By using this type of novel pressure recording equipment a precise digital pressure was collected.

3.2.2 Plantar Pressure

Plantar pressure was recorded to evaluate alterations in pressure distribution whilst walking in the different shoes. The specific research question posed (SRQ2) was to look at the effect of the shoe on the foot so a barefoot trial was essential as a baseline measure. The use of an in-shoe system could not be adopted for a barefoot condition and the use of a multi system method for pressure is not recommended due to discrepancies in data (Chevalier et al., 2010).

The pressure platform used (RsScan Int. Belgium) was embedded into a walkway of identical thickness to reduce the chances of targeting the platform and altering gait during a trial. These issues have previously been highlighted as significant in influencing data collected (Naemi et al., 2012).

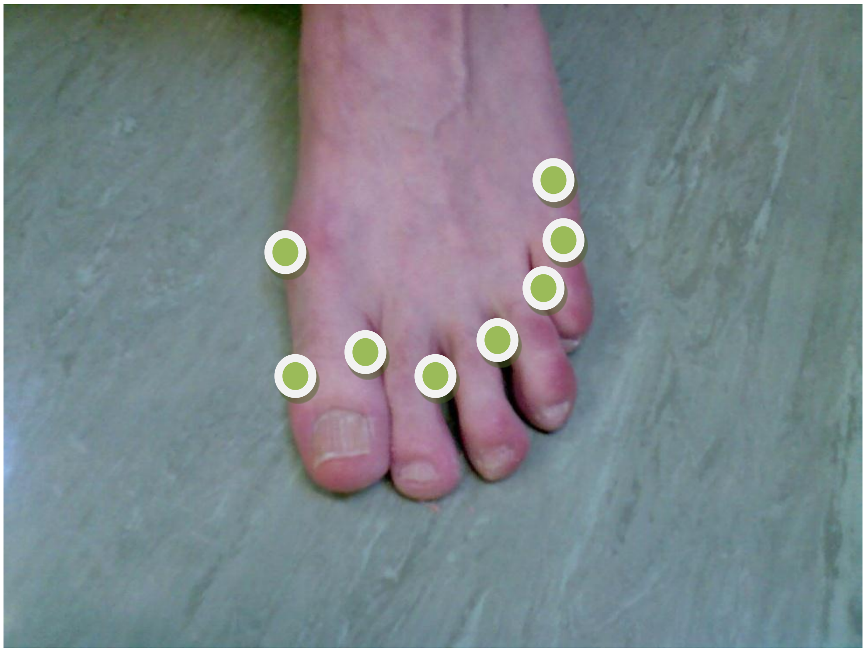

Figure 3 – Circles indicate the marker placements for dorsal and inter-digital pressure readings

3.2.3 Centre of Pressure progression

To assess and record a measure of dynamic function, the Centre of Pressure (COP) progression was identified as a measure of stability, pronation and supination (Chui et al., 2012). Calculations of COP displacement from the longitudinal axis of the foot (defined as the axis from the mid portion of the calcaneus through to the apex of the 2nd digit) during the stance phase of gait indicated specific motion of the foot. A medial deviation can be correlated with pronation of the foot and a lateral deviation can be associated with supination. Utilising this aspect of plantar pressure data allowed for a further dimension of foot function to be investigated. Gait phase timing was used in keeping with previous work on this different approach of gait assessment (Chiu et al., 2012).

3.2.4 Comfort Scale

Footwear comfort is thought to be important for shoe wearers as it is an influential factor in preventing the development of superficial foot pathology and reducing injury (Mündermann et al., 2001). The results from *Publication 7* indicated that comfort was a key part of footwear choice and has also been suggested as an indicator to the suitability of the shoe fit (Mickle et al., 2010). As comfort is a subjective measure, assessment needs to be addressed in an individual way. Visual analogue scales (VAS) have been used to measure human perception in a number of specialties. Comfort scales utilising VAS were made popular and validated in the biomechanics community by Mündermann et al., (2002). An overall comfort score can be generated by a multifaceted group of individual scores which can be modified to specific subject areas. In *Publications 12 & 14* the comfort scoring VAS was modified from Mündermann et al., (2002) to include specific areas of the shoe with a final score depicting an overall shoe comfort. By segregating the comfort scoring in this way the results collected were analysed as an overall measure of comfort but also separated to look at specific regions of the shoe i.e.: toe box comfort.

3.2.5 Shoe Characteristics

Defining a rigid protocol for footwear testing has been recently highlighted as an essential part of any research on footwear (Fredrick, 2013). However, large variations between research groups leave standardising shoe characteristics as an ongoing challenge. Barton et al., (2009), developed a clinical protocol to allow footwear to be assessed within the clinic. Many of the measures validated are subjective, relying on the experience of the clinician as an assessor, and do not allow for quantifiable measures to be obtained. To address this issue and in order to assess the specific characteristics of the ballet pump shoes in a methodologically robust manner, a variety of methods were chosen in an attempt to provide a coherent set of measurements of the shoe. The measures that were chosen were considered most effective in order to answer the research question posed (SRQ2).

Firstly, the length and width of the shoes were measured as per Barton et al., (2009). The volume of the shoe toe box was calculated by filling the toe box to the vamp of the shoe with a fine substance then weighing the quantity and determining the volume.

This simple and convenient method allowed for evaluation of toe box volume including variations in the style. These measures were then correlated to the overall shoe comfort score as well as specific comfort based scores on toe box and width. Digital scanning of the shoe would have provided an advanced assessment of the volume and dimensions and is being considered for future projects within the department that are assessing footwear fit in pathological populations. [2]

Cantilever bending stiffness (Figure 4) was also measured to determine the flexibility of the sole. Metatarsalgia has been associated with ill-fitting shoes and sole stiffness (Burns et al., 2002) and sole stiffness is frequently assessed subjectively (Barton et al., 2009). By defining a strict protocol in this research, the bending stiffness became a valid and repeatable measure that enabled the flexibility of the sole of the shoe to be quantified. Since this publication further developments within the department have been made by creating a tool and developing a protocol for measuring torsional stiffness of footwear.[3]

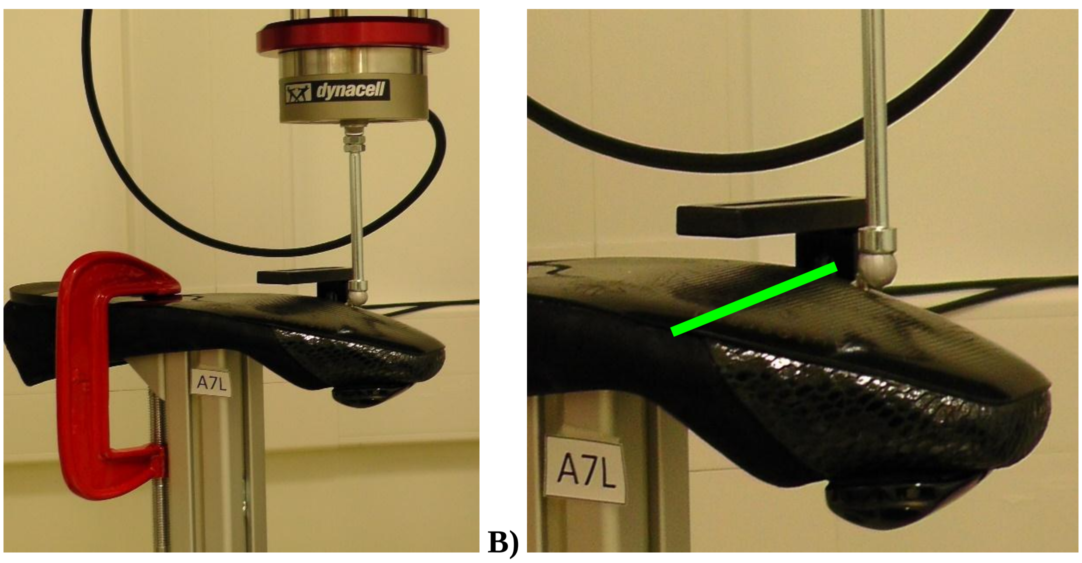

Figure 4 – Cantilever Bending Stiffness assessment of the square shaped shoe A) demonstrates how the shoe was secured to the vice and B) The line highlights in which plane the shoe was flexed

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[2] Funmi Oke, Do we wear the correct size of shoe? MSc Dissertation 2015

[3] Branthwaite et al., Torsional stiffness of Footwear, development of test method and protocol 2015

3.3 Results and Discussion

3.3.1 Dorsal Pressure

The styling, shape and volume of the toe box is often thought to be the culprit when ill-fitting shoes cause digital skin lesions. Misshaped digits due to pathology can increase dorsal pressure and the skin becomes irritated from the upper of the shoe (Bowling and Grundy, 1997). The ballet pump shoes with different forefoot toe box shapes tested in this work highlighted that a round style shoe produced the least amount of pressure on the medial side around the 1st digit and interdigital 1 and 2. The pointed shoe produced the least amount of pressure along the lateral border of the foot and 5th digit. Therefore, advising patients to purchase round or pointed toe boxes dependent on lesion site will assist in appropriate footwear suggestions. Similarly, these results could aid footwear designers to implement this shaping when manufacturing footwear that conforms to the shape of the foot, with a round toe at the medial aspect of the shoe and a pointed style to the lateral aspect of the shoe. This design should be particularly considered as most shoes available on the high street have a uniform toe box shape for each side of the shoe (Figure 5a) and adaptations in shape (Figure 5b) as seen in bespoke shoe styles could be of use.

A) **B)**

Figure 5 – A) A pointed shoe with each side of the toe box being the same pointed style, B) A bespoke boot made with the medial border being round and the lateral border pointed.

Some athletic footwear has already adopted a foot shaped toe box with particular attention to shape and structure. The Altra® shoe conforms to the foot's natural shape and is marketed as a barefoot running shoe. However, these concepts that are warmly welcomed by athletes and sports performers do not often filter down into high street shoe shops and the larger population. Furthermore, the availability of everyday shoes that fit to this shaping are often difficult to find and lead to inappropriate choices being made by consumers to conform to the current style.

3.3.2 Plantar Pressure

Alterations in plantar pressure were observed between test conditions, specifically between the barefoot and three shoe conditions. The observed changes in plantar pressure when placing a shoe on the foot are predictable, but the differences that occur between shoes of the same style are less obvious. The pointed shoe displayed a persistent higher peak pressure in the masked region of medial heel compared to the other shoe styles. This was concluded to be due to the styling of the heel counter and heel of the shoe which was discreetly different to the other two styles tested. This difference however may not be noticed by consumers who would evaluate the shoes as the same style therefore exposing them to significant differences between shoes. Another significant difference for the pointed shoe was seen as an increased contact time at the 1st digit. Compromised fit of the shoe at the forefoot with compression of the digits could have increased the amount of time spent on this digit. These significantly observed changes between shoe styles demonstrate that there are subtle structural differences that consumers are not aware of when purchasing shoes.

3.3.3 Centre of Pressure Progression

Barefoot walking compared to wearing a shoe alters the COP progression significantly in all shoe conditions at the designated gait timings recorded. Introduction of a shoe altered heel strike to a more inverted position and at toe off the COP progression was centralised to the longitudinal midline. These significant findings suggest that wearing a shoe improves the body's forward progression whilst walking and could help with stability, balance and walking efficiency. The substantial changes in COP progression between footwear styles may play a pivotal role in explaining why two shoes with the same style can provide a different experience to the same person. These notable differences between shoes and barefoot should be considered when giving footwear advice to patients especially when prescribing shoes to wear in the house.

3.3.4 Comfort Scale

Specific areas of the shoe comfort (overall shoe, width of shoe and toe box) were individually correlated with physical characteristics of the shoe. Data analyses found no statistically significant correlations were found (Table 4). A small positive statistical relationship was noted between overall comfort and the bending stiffness of the round shoe which was found to be the least stiff of the three shoes tested (refer to section 3.3.5). This small but interesting association could suggest that in a non-pathological group a flexible shoe sole is more comfortable than a stiffer sole. A stiffer shoe is often suggested for patients who suffer from painful hallux limitus to support flexion of the metatarsal during propulsion to ease symptoms (Smith et al., 2000).

It has also been suggested that the range of motion available at a joint aligns with the flexibility of the sole of the shoe, therefore a stiffer shoe for a joint pathology facilitates a relationship between shoe and foot reducing pain (Oleson et al., 2005). Footwear advice should take into account the range of motion at the metatarsals when considering flexibility of the sole of the shoe. Current manufacturing trends have leaned towards soft flexible soles in comfort ranges. However, in an asymptomatic foot a soft soled shoe may exacerbate symptoms when there is a limited range of motion in the forefoot. Being advised to avoid this style of footwear could prevent symptoms.

It was an unexpected result to see that the reported overall comfort scores for the shoes were not significantly different between conditions. A possible explanation for this was that the population included in the study did not find this style of shoe comfortable regardless of shoe toe box style, as the mean overall comfort score was less than 50% comfort on the defined scale. Inclusion of the subjects' own preferred footwear as a baseline measurement would have provided an accurate comparison of comfort.

3.3.5 Shoe Characteristics

Shoe dimensions and cantilever bending stiffness revealed significant differences between the shoes tested. These results indicated that, although the shoes at first glance looked very similar and showed the same marketed shoe size, the length, width, toe box volume and cantilever bending stiffness between shoes altered (Table 5). In clinical practice it is not uncommon for patients to report that shoe sizes differ between shops. Buying different size shoes to suit fit and comfort was observed as a buying habit in the footwear choices paper (*Publication 7*).

However, it is not current practice to provide consumers with details about the shoe's physical characteristics other than materials used to manufacture the shoe. To feature every shoe's length, width and volume would not only highlight the differences between styles but would be of little value to consumers without health education as they have no knowledge of which of the individual characteristics are suitable for their personal requirements.

Table 4: Spearman rank (rho) correlation coefficients for correlation between overall, width, toe box and length comfort scores and individual shoe characteristics. Negative values are showing a negative relationship, strength of relationship determined by small r = 0.10 to 0.29 medium r= 0.30 to 0.49 and large r =0.50 to 1.0

Shoe type	*Characteristic*	*Comfort*			
		Overall	Width	Toe box	Length
Square	Length	-0.239	-0.244	-0.25	-0.067
	Width	-0.239	-0.244	-0.25	------
	Volume	-0.239	-0.244	-0.25	------
	Stiffness	-0.126	-0.176	-0.162	------
	Cop progress	-0.055	-0.155	0.075	-0.171
Round	Length	0.020	0.202	-0.010	0.069
	Width	0.020	0.202	-0.010	-----
	Volume	0.020	0.202	-0.010	-----
	Stiffness	0.357	0.182	0.117	-----
	COP progress	-0.18	0.038	-0.228	-0.190
Point	Length	-0.209	-0.051	-0.229	-0.238
	Width	-0.209	-0.051	-0.229	-----
	Volume	-0.157	0.006	-0.146	-----
	Stiffness	0.209	0.051	0.229	-----
	COP progress	-0.066	-0.176	-0.363	-.275

The role of the practitioner delivering footwear advice as part of a management plan is to have an advanced understanding of the impact that various shoe characteristics have on function, comfort, image and pathology. An essential part of the care of patients with foot pathologies is providing individuals with bespoke recommendations as to what to look for when purchasing shoes. The future for footwear design however may change the availability of choice with advanced technologies in CAD and 3D printing allowing for individual specification when buying shoes from the high street stores. Additionally, a culture change regarding the use of shoes for fashion and image should be encouraged through footwear education in younger generations as seen in dentistry where teeth brushing in younger generations is accepted as essential to prevent tooth decay.

Table 5: Shoe characteristics, measures of length, width, volume and bending stiffness with SD and significant p values (*p*<0.05)

	Length (mm)	Width (mm)	Volume (mm^3)	Bending stiffness (Nm/deg)	Work input (Nm*deg)
Square	250.75±12.39†§	80.75±3.78†§	58.75±10.9	0.105±0.006†§	16.6±1.4†§
Round	252.5±15.8‡§	78±3.91	46.25±7.76‡§	0.056±0.021	10.7±1.6
Point	258.5±9.81†‡	78.5±3.11	58±10.1	0.072±0.010	12.5±2.1
P value	0.0005	0.0005	0.005	0.0003	-----------

* ANOVA
† significantly different to round
‡ significantly different to square
§ significantly different to point

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3.3.6 Critique

The sensors used in *Publications 8,10 and 11,* although ultra-thin, did not bend easily and therefore did not fully contour to smaller digits, and additional adhesive was required. This methodological inaccuracy may have distorted the presented results. Development of single sensors with flexible material would assist future research and can increase the accuracy of single cell pressure readings.

Measuring mechanical function through COP progression is a novel assessment method that is not frequently used. Collecting kinematic data would have been more suitable but the ongoing issue of marker placement and integrity of the shoe makes this option restrictive when looking at footwear effects. Although, this method of motion analysis is used by many researchers to look at footwear these issues continue to be a point of discussion.

In general the chosen shoe that was tested for comfort was not deemed as comfortable by the group. This shoe was chosen as the popular shoe of choice but no recruitment measures were taken to see if the subjects wore the test shoe by choice as a comfortable shoe. Altering this inclusion criterion in the sample tested, to include only subjects who wore the shoe by choice, may have reduced variability and diversity of data. The subjects also only had a short space of time to evaluate the comfort of the shoe. This is however a replica of the situation observed in a shoe shop when trying on a shoe to purchase. A more effective way to buy shoes would be to spend a full day or more wearing the shoe to assess comfort prior to agreeing to continue to wear the shoe. This can be done indoors and most retailers will take footwear back if it is not worn outside.

3.3.7 Contribution to knowledge

Development of the initial method presented in *Publication 8*, of a single sensor pressure protocol, has enabled significant results to be reported regarding the relationship between shoe shape and dorsal toe pressure. This type of data collection has not been previously reported on and the impact this paper has had on the collective audience is shown in the available statistics, with 3015 downloads over the 5 month period after its initial publication in July 2013. Social media has also picked up on the work in 4 separate tweets and there has already been four citations in peer reviewed publications. This highly accessed work demonstrates the high interest in the mechanical effect of everyday footwear on the foot.

Similarly, COP progression *(Publication 14)* has previously had little attention. However, since publication of this paper further studies have also adopted COP progression for analysis of dynamic movement (Bizovska et al., 2014, Lugade and Kaufman 2014). This technique for analysis overcomes the restrictions of kinematic analysis with marker sets.

Comfort as a measure has been studied in many health-related themes from pain management to treatment outcomes and intervention. Utilising a comfort scale to look at footwear has not been used to a great extent and the flexibility of generating an overall comfort score as well as segmenting the score into specific shoe sections allowed for an in-depth analysis. This work has added to ongoing work on footwear effects and how shoes are perceived for comfort.

3.4 Conclusion

Footwear shape and, in particular, toe box styling plays a significant role in the amount of pressure around the toes. Footwear advice given to patients for the management of painful foot conditions should consider the impact the shoe toe box shape will have on dorsal pressure as well as stability. Further work should look at quantifying the threshold of dorsal pressure required to develop callus and superficial skin pathologies, as well as understanding of the role footwear plays in developing these cumbersome problems. Additionally, manufacturers of footwear should encompass the round toe shape on the medial side and the pointed shape on the lateral side further into high street footwear designs to expand the suitable choices available to consumers.

The comfort of a shoe is complex, multi-factorial and has many features. The ballet pump shoe is not deemed comfortable by all users and the shape of the toe box does not influence comfort. However the flexibility of the sole is related to comfort with a small effect and could be related to the range of motion available at the forefoot. The structure and physical characteristics between the shoes tested were significantly different even though at first glance all the shoes looked and felt very similar. Consumers are unaware of these altered characteristics when purchasing shoes and rely on comfort and fit as an indicator to the suitability of the shoe for use. Advanced health education regarding footwear could improve consumers' experiences when buying shoes and also develop an awareness of shoe properties that could be beneficial to foot function.

Chapter 4

The effect of wearing an unstable shoe

4.1 Introduction

It has been established that the colour of the athletic shoe influenced most footwear purchases (*Publication 1*) and fashion and trends are also considered to be important (*Publication 7*). Over the last decade, attempting to improve health by wearing specific exercise shoes has been a popular choice *(Publication5)*. From the key note lecture presented as *Publication 13* the effect of wearing the unstable shoe was reviewed with the main discussion focusing on how the shoe could be used in clinical practice for rehabilitation. Footwear that is marketed as unstable promotes itself as a mean to increase muscle activity, alter posture and improve balance for the user. The reported effects of wearing such shoes do support these marketing claims in some studies (Romkes et al., 2006, Nigg et al., 2006), but others have reported varying results (Landry et al., 2010). Previous research has often given the subjects a training period to acclimatise to the shoe prior to testing, but the effect of the shoe on muscle activation could be instantaneous and this period of training may not be required.

The aim of the following publications was to evaluate the immediate effect of wearing the MBT® for the first time as well as to explore the potential for its use as a treatment modality.

Table 6: Synopsis of Publications 4,6 and 9

Publication	Appendix	Overview	Contribution to Knowledge
Branthwaite, H.R., Naemi, R., Chockalingam, N. (2010). The effect of negative heel profile shoes on triceps surae**. International Foot and Ankle Biomechanics- i FAB** Seattle, USA. September.	**4**	The concept of using the unstable shoe as a training device was investigated as a small pilot study. Alterations in ankle kinematics were observed during the segment of the gait cycle where eccentric loading of the triceps surae occurs. This observation could suggest that the MBT® shoe could be used as an effective treatment for	Applying the known effects that have previously been reported to the use of the unstable MBT® shoe as a treatment option allowed for exploration of unique and alternate approaches to Achilles tendon pathologies.

		Achilles tendon pathologies	
Branthwaite, H.R., Pandyan, A., Chockalingam, N. (2012). **Function of the triceps surae muscle group in low and high arched feet: An exploratory study.** *The Foot,* 22(2), 56-59.	**6**	Monopolar electrodes were explored to devise a protocol for EMG activity of the triceps surae group in different foot types. This paper investigated extremes of foot type and Achilles tendon anatomy for links between form and function.	Foot posture and triceps surae muscle function is related. Alignment of the rearfoot could alter the muscle function due to configuration of muscle fibres into the Achilles tendon.
Branthwaite, H.R., Chockalingam, N., Pandyan, A., Khatri, G., (2012). **Evaluation of lower limb electromyographic activity when using unstable shoes for the first time: A pilot quasi control trial.** *Prosthetics and Orthotic International*. 37(4), 275-281.	**9**	Expanding from the triceps surae EMG protocol, to include other lower limb muscles, the effect of wearing the MBT® unstable shoe for the first time were researched. Variability in data suggested that some individuals have no immediate response to wearing the shoe, others have increased activity and a third group have decreased activity of the muscle groups tested.	At date of publication previous work had not investigated the effect of instantaneous muscle response to wearing the MBT® unstable shoe. Similarly muscles that had not previously been investigated were included for changes in activity.

4.2 Method

4.2.1 EMG

To understand muscle function and variation between individuals a small exploratory study was conducted using monopolar electrodes (*Publication 6*). This protocol was then modified and utilised to investigate the impact of wearing an MBT® shoe. Using a repeated measures design, *Publication 9* investigated the immediate effects on lower limb muscle activity whilst wearing the MBT® shoe for the first time. The instant change in EMG activity was explored as it is not known if muscles respond immediately to an altered environment or whether a period of training is required, as adopted by most methods (Nigg et al., 2006, Romkes et al., 2006). EMG recordings were taken from selected lower limb muscles based on previous work as well as activity from muscles not previously reported (Nigg et al., 2006). The EMG data collected was clean with no interference. This data was notch filtered and rectified prior to passing through a 10-Hz eighth-order Butterworth filter and analysed on a bespoke program through MathCAD (Version 15; PTC, Needham, MA, USA).

Eccentric loading of the triceps surae muscle is accepted as being the most effective treatment of Achilles tendinopathy (Nørregaard et al.,2007). Using the MBT® as a training device was explored (1.6.Aim 3) to evaluate if eccentric loading of the triceps surae group increased when wearing the shoe. Lengthening this group of muscles with increased ankle dorsiflexion would alter the function of the muscle during walking. Simple repeated measures whilst walking were completed as well as performing the eccentric exercises as reported by Nørregaard et al.,(2007).

4.3 Results and Discussion

4.3.1 EMG

The results from these studies showed a large amount of variability between the subjects investigated with no systematic response, especially when the MBT® shoe was worn for the first time. *Publication 4*, being a pilot study, demonstrated interesting scope for further clinical trials. Since the publication of this work, further papers have reported and referenced this work on the feasibility of the MBT® shoe being utilised as a treatment. These include the use of the shoe being beneficial to the recovery of athletes after marathon fatigue (Nakagawa et al., 2014) reduction in lower back pain (Armand et al., 2014) and it also has been shown to reduce ankle plantarflexory moment in Achilles tendinopathy (Sobhani et al., 2014) suggesting that there is a clinical use for such a shoe.

From studying the immediate impact of wearing the MBT® shoe (*Publication 9*) it was noted that some of the group had an increase in muscle activity; others a reduction and a final group had no change. This large variance between subjects resulted in no significant difference being observed when wearing a MBT® shoe for the first time. If, however, the overall mean results are investigated in isolation then the following muscles were seen to have an observed increase in activity:

- Soleus,
- Medial gastrocnemius,
- Peroneus longus,
- Rectus femoris,
- Gluteus medius.

Lateral gastrocnemius remained the same and tibialis anterior and biceps femoris reduced in activity whilst wearing the MBT® shoe (Table 7). But if the results are examined on an individual basis these muscles did not respond in this generalised way in all subjects, resulting in the large variability seen. Similar increases in activity have been observed after wearing the shoes for a training period of four weeks (Nigg et al., 2006, Romkes et al., 2006), suggesting that in some subjects the response to wearing this instability shoe is immediate and the necessity for a training period is not required.

Table 7: Mean, Maximum EMG (mV) and percentage values for each muscle for each condition. Paired t-test significance for Mean *p* value. *(SOL =Soleus, MG=Medial gastrocnemius, LG= Lateral gastrocnemius, TA= Tibialis anterior, PL= Peroneus longus, RF= Rectus femoris, BF= Biceps femoris and GMed= Gluteus medius).*

Muscle	**Shoe**			**MBT**			**t-test**
	Mean	max	%	mean	max	%	P value Sig(p<0.05)
SOL	68.908	245.446	32.018	91.259	250.566	39.934	0.168
MG	68.598	250.741	32.399	79.468	327.407	28.772	0.25
LG	132.624	626.55	25.39	134.541	619.734	28.321	0.942
TA	89.081	279.386	31.956	66.363	214.375	34.465	0.299
PL	67.915	254.676	30.495	79.371	285.332	30.129	0.225
RF	515.012	1648.816	32.197	705.203	2256.528	29.234	0.149
BF	287.006	957.947	28.774	190.186	581.783	30.231	0.149
GMed	94.053	307.764	30.431	195.034	627.294	30.621	0.101

4.3.2 Critique

The lack of a systematic response to intervention demonstrates the large amount of variability naturally observed within human populations. Increasing the sample size studied may have increased the strength of any relationship present or similarly it may have enhanced the observed results reported indicating that there will always be a positive increase in muscle activity in some people, another group will always have a decrease and then a group will have no change. The same results are also reported by other groups whose sample is from larger populations (Sacco et al., 2012. Forghany et al., 2012) when using MBT® in a variety of ways.

4.3.3 Contribution to knowledge

At the time of submission this paper appeared to be the first to investigate the instantaneous response of muscle activation when wearing the MBT® shoe for the first time and as a treatment option. Since completing this work other publications have also investigated the immediate effects of wearing the shoe with similar results (Sacco et al., 2012) and as a treatment modality (Nakagawa et al., 2014, Armand et al., 2014). Not only has the work included in this published work shown a further understanding of how the MBT® shoe alters EMG activity, the 2 publications were original at the time of writing and have now been expanded by other research groups.

4.4 Conclusion

The MBT® shoe is available on the high street and internet for consumers to buy with no prior knowledge about the long term effects of wearing the shoe or, even worse, how each individual will respond to the changes it brings about. Consumers are unaware if the shoe will make an immediate effect on muscle activity or no effect at all. This costly item that claims to improve posture and stability does not demonstrably have an observable or measurable impact on muscular activity as shown from the results of this paper and others. Further knowledge of how to evaluate the response of an individual whilst wearing this style of shoe will ensure that consumers are not misled into purchasing a shoe that will have no positive effect for them or, even worse, could be detrimental to their health.

Chapter 5

Ethical and Data Considerations

5.1 Ethical Procedures

All of the research studies referred to in this thesis were approved by the Research Ethics Committee at Staffordshire University prior to the commencement of the projects undertaken. Subjects involved in the studies were given relevant information sheets and the opportunity to ask questions prior to written consent being taken. All subjects were made aware that they were able to withdraw at any time, without giving a reason, and any of the data collected at any point in the study would be destroyed. Where necessary, data was anonymised and access to all data collected was only accessible via password-protected PC (Appendix 15).

5.2 Data Analysis

Obtaining a representative sample of an adequate size to study determines the power of the results and conclusions made within the paper (Petrie & Sabin 2009). These factors are also influential in statistical significance and probability of the hypothesis being accepted or rejected.

To gain a significant result on opinion-based questionnaires of fixed design, a sample size of above n=100 for each of the major outcome measures being investigated is required (Borg and Gall, 1989). Both questionnaires (*Publication 1&7*) were delivered to samples of n=195 and n=162 respectively. These larger samples were deemed significant in size and power in terms of establishing the presence or absence of statistical significance. However, as each of the questionnaires tested more than two outcome measures per questionnaire, a greater number of participants would make the results more reliable. Therefore, interpretation of these works should consider the sample size and population represented when discussing the results.

The papers that focused on footwear testing were designed to compare the effect between conditions and explore potential differences. Therefore statistical testing comparing means was used for data analysis. When comparing means, a lower sample size can be used to gain significance with a recommended minimum number of 20 subjects. However, this figure is dependent on the level of normality tested (Pallant, 2010). Testing for *Publication 10-12 &14* were completed on a convenience sample size of n=27, which fits to this minimal value but similarly, as multiple levels of factors were investigated this could impinge on the strength of the relationships observed.

Other Publications which were exploratory for methodology used a smaller sample and the impact of this is described in the discussions. (*Publication 4,6,& 9*)

Additional to the challenges of correct sampling, during analysis there was a discrepancy between variables in the data meeting all the assumptions set for parametric testing. This was particularly evident in the publications concerning pressure data. It was found that the results for dorsal pressure were not normally distributed, and that further investigation indicated that this abnormality of distribution was due to the presence of zero recordings on some of the sensors that caused a skew in distribution. However, rectifying and accounting for this altered distribution would have resulted in data being presented as a negative value which is not a valid reading for pressure, i.e., it is not possible to record negative pressure. Therefore the non-parametric equivalent for data analysis was undertaken.

It must also be highlighted that all subjects that took part in footwear testing publications had no known pathology to the lower limb and represented a normal sample. Further work is recommended to build on the results reported in all this work to apply the data to a pathological sample when implementing footwear advice and effects into treatment plans.

Chapter 6

Conclusions

Footwear plays a key role in image and fashion for young female populations. The comfort of the shoe plays a significant role when choosing a shoe yet discomfort is tolerated enough to keep up appearances in certain styles. Toe box styling does not appear to alter comfort as initially thought. Shoes can alter human gait and the physical characteristics of a shoe often impact on dorsal and plantar pressure. Footwear advice is a critical part of patient care and should be considered for every clinical assessment. Individual needs should be matched to footwear styles as well as physical characteristics and consideration should be given to the role footwear has in self-awareness, image and fashion as well as function.

In general the results from this collection of published work can conclude:

1. Footwear can be used as a treatment for foot pain on an individual basis with appropriate assessment, but the exact cause of foot pain related to ill-fitting footwear needs to be studied further.
2. The impact of an unstable shoe on muscle activity shows high variability and not all individuals respond in the same way.
3. Footwear choices for younger females are based on the activity or occasion that the shoe is to be worn for with comfort and the feel of the shoe being the most important factors considered.
4. The most popular shoe for everyday use in younger females is a flat ballet pump shoe yet not all people find these shoes comfortable. However, this style of shoe with a flexible sole is more comfortable than a stiffer soled shoe.
5. Shoe toe box shape can influence digital and plantar pressure and a shoe with a round edge on the medial border and a pointed lateral border may produce the least amount of toe irritation related to pressure.
6. Shoes alter COP progression significantly and improve gait at heel strike and toe off highlighting that barefoot walking is not always the most efficient.
7. Physical shoe characteristics can vary between shoes of the same style and genre. Advanced understanding and knowledge is required for individuals to purchase shoes that are of use.

6.1 Implications for Clinical Practice and Future Research

Although this work did not assess current practices of footwear advice amongst healthcare professionals, it can be concluded from clinical experience that often this advice is based on the clinician's experience and training as well as personal preference rather than original research. The results from this collection of work have begun to enrich the knowledge regarding the effects of everyday footwear and have already led onto further work in this field.

Dissemination from publications, conferences presentations and key note lectures has prompted self-reflection in clinicians who are involved in footwear advice. The information exchanged has influenced the thought process of a range of clinicians who have engaged in this work and in turn has impacted on their own clinical practice. Although this has not yet been investigated in a structured fashion, discussions and feedback has demonstrated a change.

The inclusion of image, styling and footwear structure will positively influence the change of footwear habits in individuals who are advised appropriately. In turn this advice will advance the education of patients who have footwear related pathology, but will also progress to influence choices in younger generations prior to severe deformities arising. Footwear designs available to consumers should provide a greater choice and variation in sizing and shape around the toe box to prevent the progression of footwear related pathologies.

Research developments around the area of pain related to everyday footwear needs now to investigate the impact of footwear choice on a clinical population and aim to advance the knowledge around the role shoes have in foot health. This work has already commenced within the department and there are plans to continue to explore mechanisms involved in footwear related pathologies. Presentation of the current research and ongoing studies around footwear in peer reviewed journals and multidisciplinary conferences will ensure that the findings of this work are disseminated appropriately. Similarly, the findings can be used with the support of industry to generate funding and interest into the continuing problem of footwear choice for the general population.

6.2 Summary of contribution to knowledge

The collection of publications presented in this thesis have improved the understanding of the effects of everyday footwear on foot function and has also investigated the potential use of footwear as a treatment intervention in the following ways:

- This collection of publications is one of the first to examine current opinion on footwear choice and scrutinise the decisions young people make when purchasing shoes. The main highlights are that sports shoes are purchased based on colour and everyday shoes are bought for purpose, with a ballet flat being the most popular shoe.
- The work has developed a new and innovative method to measure individual dorsal pressure readings which has not previously been used. Footwear was assessed in a new dimension, showing that a round style of toe box has a reduced amount of pressure at the 1^{st} toe and a pointed style of toe box has reduced pressure at the lesser toes.
- This work has revealed that the stiffness of the sole is considered more comfortable when it is flexible by a young healthy population and shoe width and length do not influence comfort perception of a shoe.
- A large amount variance in the immediate muscular response is observed when wearing an unstable shoe for the first time and individuals do not react in a uniform way suggesting that this footwear is not suitable for everyone.
- Footwear advice, as part of a treatment plan could be individually prescribed according to the presenting complaint and should consider forefoot shape, range of motion of the metatarsals, COP pressure progression and style and image choices of the individual.

Whilst previous published literature have looked at the effects of footwear in specific clinical conditions and in their clinical management (Chuckpaiwong et al., 2009, Mickle et al., 2011, Armand et al., 2014,), the work within this thesis takes a different approach and examines the primary causative factors for perceived long term footwear related pathologies. This collection of publications demonstrates the original contribution made to understanding the impact of the choices made by young people for everyday shoes has on the foot. Additionally the work demonstrates the mechanical changes observed when physical footwear characteristics are varied.

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APPENDICES

Appendix 1

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LETTER TO EDITOR
What influences someone when purchasing new trainers?

Since *Wait Webster* applied rubber to the sole of his shoe in 1832 and developed the first running shoe, the trainer or the running shoe industry has gone through various phases of development to help athletes achieve greater performance. To date major brand names have pumped millions of US dollars into research and marketing with a view to develop shoes that alter running mechanics and improve lower limb function and to reduce injuries.

The development of the running shoe has seen many changes, starting out as a basic plimsoll and advancing to shoes that claim to address impact forces, prevents excessive motion, improve stability and increase performance. Interestingly the effects of cushioning in a shoe have not contributed to lower the peak ground reaction forces on impact; instead runners modify their running style to accommodate for the change in loads therefore altering their running style (Kong et al. 2008). A recent study indicates that a more expensive and cushioned running shoe is no better at altering the plantar pressure than a cheaper alternative (Clinghan et al. 2007). However cushioning is greatly associated with comfort and is featured in most running shoes (Mündermann et al. 2001).

Motion control is a key characteristic for many shoes with brand specific features, all of which are designed to be supportive to the medial aspect of the shoe with dual density midsoles and altered midfoot support. The aim of this feature is to reduce excessive foot pronation at midstance with the thought that having an increased motion at that point in the running cycle can instigate injury (McManus et al. 2004). In spite of this, it has been shown that a supinated foot has a greater risk for developing an overuse injury due to its rigidity (Cain et al. 2007). Yet there does not seem to be a shoe designed for an increased supinatory moment around the ankle.

One should also note that running shoes need to be lightweight and breathable as the material content of the uppers plays a key part in comfort of the shoe (Fong et al. 2007). Whilst athletes thrive on increased performance by reducing the time achieved whilst running, altering the weight of the shoe and improving temperature control provides a more comfortable experience, avoiding minor aliments like blistering and hyperhydrosis.

With all this in mind, we wanted to know what persuades athletes to go back to the shop and buy another pair of shoes that will cost them in the region of £80–£90(GBP)? If all the technology and research used in the development of the running shoes has not been shown to reduce injury or improve performance, why do people keep buying them? Furthermore, what influences someone when purchasing new trainers?

As a starting point to this discussion, we conducted a study here at Staffordshire University to assess the impact and dissemination of the research and design that goes into the development of running shoes on the athlete's decision to buy and use a new shoe. We questioned 195 Sports and Exercise students based on the thoughts, feelings and choices they made on purchasing the last set of training shoes. The questionnaire explored the type of shoe purchased, the technical factors that influenced the purchase, the qualities of the trainer, emotions associated with wearing the trainer, what the training shoe was used for and a review of lower limb injuries.

Results indicated that Adidas were the most favoured shoe brand with 58 subjects, and then 49 buying Nike, 16 K-Swiss, 9 Asics, 9 Lacoste, 2 Reebok, 1 new balance and a combination of other footwear brands was equal to 51 subjects.

Colour was deemed the most important factor when making a purchase with 151 subjects indicating that they buy shoes on the colour, the brand of the shoe they were buying was also important ($n = 128$) subjects, followed by how much cushioning ($n = 74$), type of activity ($n = 54$) and motion control ($n = 15$).

In terms of psychological parameters, 78% of subjects did not express any negative emotions when wearing the trainers with and 82% felt good wearing the trainers. Everyday wear (47%) was the most common use for the trainers, with specific sports activities comprising of running (23%), gym (21%) and other (9%, tennis/netball/football).

Results of this study indicated that the main use for training shoes is to wear them for everyday use as a normal shoe. This may be as the comfort and cushioning of the shoe is preferable to a traditional shoe and the influence of image and fashion favour the use of training shoes. The main influence on purchasing the trainer was colour and brand, again

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highlighting that image and fashion are more important factors than cushioning and motion control. There was a positive feeling experienced when wearing the training shoe, associating the use of training shoes with self esteem and image rather than improved performance and function. Clearly the impact of brand specific features and technologies that are researched to maximise performance and reduce injury are not influential for this population when buying training shoes. The influence of design and marketing dominates the thought process on purchasing a shoe and the impact of the function of the shoe is less significant.

While the results of this study inform the debate, it will be interesting to look at the views of product designers and developers. Furthermore, the effects shoe wear and it is relationship to biomechanical function needs to be explored.

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Appendix 2

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The Role of Footwear in Rehabilitation: A Review

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Abstract

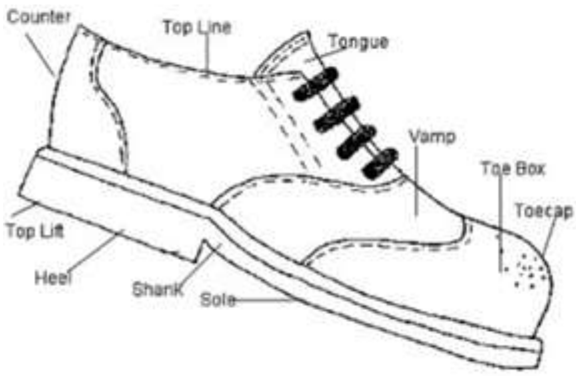
Whilst footwear is primarily used to protect the foot from cutaneous injury, its use as a therapy in rehabilitation is becoming more significant as shoes can be selected and modified to meet the clinical needs of a patient.This paper provides a general overview to the uses of footwear in the rehabilitation of patients with diabetic foot complications, rheumatoid arthritis, osteoarthritis and the elderly. Furthermore, it highlights the role footwear plays in improving function and performance.Therapeutic footwear and footwear adaptations are frequently used within rehabilitation to accommodate joint deformities, modify plantar pressure distribution, alter gait patterns and improve stability and balance. However there are limited footwear choices for common foot health problems leading to persistent problems associated with fit and comfort. The evolution of a bespoke shoe that is fit on the high street would provide an effective therapy for the masses.

Introduction

Previous reports have indicated that rehabilitating a patient to restore function can be time limiting (Nolan et al, 2000). The role of footwear in providing support to improve performance by addressing restraints associated with mobility is known amongst rehabilitation professionals. Whilst the primary function of footwear is to protect the foot from cutaneous injury, it plays a crucial role as a therapeutic device. It is often used as (i) a part of the rehabilitation process of patients in the recovery of musculoskeletal injury, (ii) a pressure relieving device in complex diabetic and rheumatoid foot complaints and (iii) an aid to accommodate congenital and developmental deformity (Janisse and Janisse, 2008).

Therapeutic footwear can be prescribed with modifications and adaptations added to a standard shoe or the shoe can be manufactured bespoke to the needs of the patient. A standard high street shoe is comprised of several variable components that will influence the style, fit and comfort (*Figure 1*). Fashionable shoes that are worn as an accessory with little function, consist of different shapes for each section that can considerably alter the style and fit of the footwear. Similarly, in high performance sports shoes the components of the shoe are modified depending on the sport and material properties of the sole can enhance performance by improving shock absorbency. However in rehabilitation and therapeutic footwear, the components of a standard shoe are modified to meet the needs of the patient. A frequent requirement being increased depth and width of the toe box (Williams and Nester, 2006). The perception of orthopaedic and prescription footwear can sometimes be deemed as unacceptable to patients as the current styles and shoe modifications are undesirable and high street shoes are often utilised in favour (Williams and Nester, 2006).

Figure 1 Components of a shoe



Orthopaedic Footwear

A Rocker sole is the most commonly prescribed orthopaedic modification for the benefit of reducing plantar pressure and removing the propulsive phase of gait (Hutchins et al, 2009, Fuller et al, 2001). Whilst reduction in plantar pressure is a desirable outcome for management of the rheumatoid foot, a previous study (Hennessey et al, 2007) evaluated the reduction in plantar pressure between an orthopaedic shoe and a normal running shoe in patients who had forefoot pain associated with rheumatoid arthritis. The results indicated that the running shoe was more effective in reducing plantar pressure and accepted as comfortable by the participants. These running shoes are normally made to standard widths and depths and hence the toe deformities often seen in rheumatoid patients may not be accommodated within off-the-shelf running shoes. However, running shoes are still a popular choice for management of foot pain in the initial phases of the disease when gross joint deformities have not developed (Hennessey et al, 2007). While, ankle fusion and severe ankle osteoarthritis causing limited ankle motion respond well with the use of rocker sole modifications, previous reports indicate that altered heel strike kinetics and an increase in toe off plantarflexion shortens the stride length and thus reduces the required motion at the ankle joint (Myers et al, 2006).

Although the use of rocker shoe modifications demonstrate desired clinical effects, previous investigations (Wu et al, 2004 and Long et al, 2007) have highlighted an increase in knee and hip flexion. Furthermore, the joints are in a flexed position for a longer period throughout the gait cycle whilst wearing a shoe with a rocker sole modification. While, potential problems that could arise from this change has not been recorded in the population who wear prescription footwear, recent research indicates increased joint flexion and time spent in a flexed position as influential factors in the development of musculoskeletal overuse injuries (Willems et al, 2006).

More complex acquired and congenital deformities, as seen in conditions such as chronic osteoarthritis of the toes, foot collapse or club foot, can require significant shoe modifications to support the foot and rebalance any asymmetry (Tyrell and Carter, 2009). Furthermore, accommodations for limb length discrepancy and fixed joint positioning can be implemented on the sole of the shoe or with in the structure of the shoe. These adaptations and modifications that are made are frequently are bespoke in design and meet the clinical needs of the patient to improve their stability and function whilst walking (Tyrell and Carter, 2009).

Diabetic Footwear

The key aim for the use of footwear in the rehabilitation of diabetic patients is to provide shoes that improve the healing and prevention of plantar and dorsal foot ulcerations. Pressure relief has been highlighted as an important component in healing of diabetic ulcerations (Piaggessi et al, 2003). The use of appropriate footwear to reduce dorsal and plantar pressure the healing time for foot ulceration improves reducing the risk of further complications. Furthermore, forefoot off loading shoes (*Figure 2*) are normally utilised in initial management of ulcer treatment as they accommodate bulky dressings and reduce plantar pressure. However, they are not perceived as comfortable shoes which could influence compliance of treatment (Bus et al, 2009).

Figure 2 A forefoot off loading shoe.

Once healing of any ulceration is achieved, the use of therapeutic/orthopaedic footwear to prevent further ulceration and tissue loss is used in the rehabilitation of patients (Bus et al, 2008 (a)). These modifications may include the use of a rocker sole, the positioning of which could be reflective of the position of any ulceration and the desired effect that is required

(Hutchins et al, 2009). Bespoke changes to the toe box, heel counter and top line are often used to improve fit and comfort of the shoe.

The use of footwear in diabetic foot ulceration is widely adopted with in clinics. However a recent review (Bus et al, 2008 (b)) concluded that although the effects of footwear looked promising, there was a clear paucity of sound studies to support the use of footwear in the rehabilitation of diabetic foot ulceration.

Physiological effects of prescription footwear

Previous investigations have documented the use of footwear to change gait kinematics and kinetics as well as muscle function and oxygen consumption (Luo et al, 2009). While, these principles are traditionally used to alter gait in a pathological population they have now become a household feature with consumers being able to influence and alter normal function with therapeutic footwear in the form of commercial branded shoes (MBT, Sketchers Shape-ups, Chung shi, FitFLop and Xsensible stretch). The explosion of products to improve posture and alter gait have been a success in the health and fitness market, with sales of the MBT shoe and Fit Flop soaring since their launch and marketing. However there is little scientific evidence to support the health benefits of wearing therapeutic footwear in the long term without an existing pathology.

Romkes et al, (2006) found changes in tibialis anterior and gastrocnemius muscle activity when wearing the MBT shoe and concluded that the footwear be utilised as a part of a strengthening exercise regime for these muscles. Similarly, Nigg et al, (2006) observed beneficial changes in tibialis anterior activity that supported the therapeutic use of rocker soled shoes.

The extent to the benefits of persistent use of such shoes is not understood or documented and could potentially be detrimental with alteration in muscle activity and gait patterns. There is a possibility that these changes become irreversible and normal high street footwear unusable.

Footwear and Falls

Ambulation in an effective and safe manner plays an important role for the advanced rehabilitation of patients whose gait has been affected by their health and in the elderly population. Balance and stability are often key parameters that can influence how rapid the progress of normal walking is achieved. Stability of footwear can influence the balance of the patient. Menant et al, (2008) highlighted that the composition of the sole of a shoe caused changes in the base of support and recommended that elderly people who were at risk of falling should wear shoes that had a low collar and standard sole stiffness, with or without treads to increase stability. However Decker et al, (2009) found that there was a reduction in coordination with lower traction (grip) of the shoe. This would then increase the risk of falls. It is unclear which is more beneficial for preventing falls as an increase in traction may induce a stumble in an elderly patient whose gait is compromised towards a shuffle and a reduced traction would aid this shuffling gait.

Nurse et al, (2005) recommended the use of a textured insole in therapeutic footwear as they observed an improvement in sensory feedback and reduced muscle activity, thus improving proprioception and stability. It would be a suitable conclusion to implement a combination; incorporating a textured insole into footwear and having a sole with moderate traction to improve the stability and function.

Foot health

Foot health problems are prevalent in the elderly population with females suffering more than men (Benvenuti et al, 1995). Advanced arthritic toe deformities including hallux valgus, hammer toe, and joint subluxation cause problems with standard toe box depths and widths. High street footwear that accommodates these problems are normally difficult to obtain causing an increased tendancy for ill fitting shoes to be worn. Menz and Morris (2005) recommend that footwear assessment should take place when assessing the needs of elderly patients as ill fitting footwear was a prevalent problem for this population. More recently Mickle et al, (2009) reported that the available shoes for the elderly population was limited, increasing the risk of injury. This report also indicated that the manufacture of such shoes was inadequate for females as the shoes manufactured were a scaled down version of the lasts used for gentlemans shoes leading to compromised toe box and problems with fitting.

Footwear style and choice do play a role in injury rehabilitation and it is an essential therapy to be utilised when treating patients with common musculoskeletal complaints which have been associated with poor fitting footwear (Dilnot et al, 2003; Yu et al, 2002). Over the centuries increases in heel height and narrowing toe boxes have been blamed for causing musculoskeletal injury (Menz et al, 2005; Luo et al, 2009). Furthermore, previous research indicates that the incidences of forefoot neuroma's are higher in females who wear shoes with a narrow toe box (Menz et al, 2008; Balint et al, 2003). Lateral compression at the forefoot alters metatarsal function compressing the nerve causing an impingement injury. Altering footwear style in the early stages of the complaint relieves symptoms and prevents further development of scars (Llanos et al, 1999).

It is known that plantar heel pain can be aggravated when footwear changes the foot position and function. Hence symptoms do not resolve when inappropriate footwear is worn. Addressing heel height, either by reducing or increasing, will alter the mechanics of the Achilles tendon and plantar fascia which are well documented as being the primary tissues involved in patients who have plantar heel pain (Burnfield et al, 2004; Rajput and Abboud, 2004).

Forefoot equinus, a foot shape that is commonly observed, presents when the forefoot lies in a plantarflexed position to the rearfoot. (Figure 3) When placed in flat shoes this actively dorsiflexes the midtarsal joints jamming and compacting the metatarsals against the cuneiforms. Over time continual stress and repetitive trauma damages the joint leading to the 1^{st} stages of osteoarthritis. Wearing a shoe that has a suitable gradient in the shank (to accommodate for the lowering of the forefoot) and appropriate heel height will reduce the dorsiflexing moment and relieve any compression on the midtarsal joint complex. A heel over the height of 5cm is thought to compromise muscle action and lower back stability. Murley et al, (2009) reviewed the influence of footwear on muscle activity and found that changes in fatigue occurred in heeled shoes particularly in the gastrocnemius muscle and lower back muscles. Heeled shoes are well documented as being detrimental on stability, muscle and tendon length, pelvic alignment and forefoot pressure (Hewitt et al, 2009; Speksnijde et al 2005; Lee et al, 2001).

Figure 3 Forefoot equinus shape, the forefoot is lower than the rearfoot.

Discussion

The choice of footwear can be debilitating if an incorrect style and type is worn. Changing this to suitable shoes limits the progression of common foot deformities and reduces discomfort from superficial irritation. Furthermore, choosing to wear an appropriate pair of shoes initially could help in the prevention of general foot health complaints. Therapeutic footwear will continue to develop to aid and rehabilitate those who have significant systemic disease that inhibits sensation, balance, gait permutation and are unable to wear mass produced shoes.

The less complex problems that the general population suffer from are currently not as simple to manage with footwear. The prospect of being able to purchase footwear from a high street retailer specific to your needs, either preventative or therapeutic, should be a feasible option for people over the next decade.

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Appendix 3

Footwear the forgotten treatment.   Britpods 2010

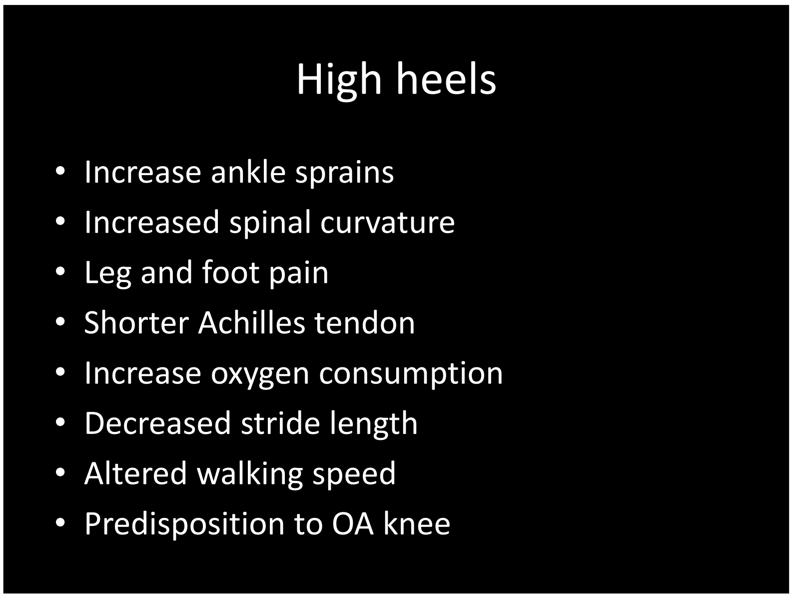
This key note lecture was given to an audience of 60 Podiatrists during a 2 day conference/workshop on footwear. The key aim of the lecture was to emphasise the use of footwear in the treatment of common foot pathologies as well as introduce and discuss emerging trends and concepts.

The forty five minute presentation reviewed the history of footwear and looked at how the styling and fabrication of shoes had evolved over time. It then considered the concept of what shoes are chosen for either function or fashion, discussing the reported literature of what happens when ill-fitting footwear is worn.

The main body of the presentation centred on the reported changes that occur when wearing fashion shoes and how in certain conditions this may be of use to the patient. For example in heel pain and Achilles tendon dysfunction a heeled shoe is useful to off load the posterior structures of the leg. In contrast to this discussion, the presentation continued by introducing to the audience the potential use of functional unstable shoes in the management of musculoskeletal lower limb pathologies.

Finally footwear assessment and fit as well as the type of advice podiatrists offer to patients was presented and how this advice should be tailored to each patient to help manage the presenting complaint.

The full power point presentation can be viewed on request if required. Below are a number of the key slides to demonstrate the type of literature presented.



Science

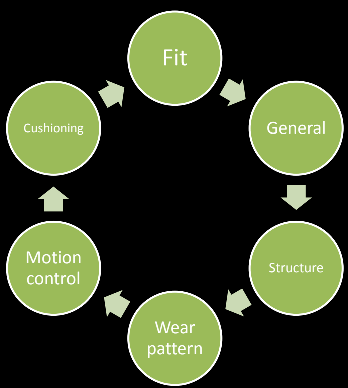
- MBT most studied
  - Reduces neuromusuclar variability
  - Altered EMG of Tib ant and gastroc (Romkes et al 2006)
  - Shifts foot pressure anteriorly (Stewart, et al 2007)
  - Suggested to alter OA pain and improve muscle use (Nigg et al 2006)

Footwear the new orthoses?

- Orthoses

*are devices that support or correct musculoskeletal deformities and/or abnormalities of the **human body**.*

Analysis



How shoes can be used.

- Toe box Shape
- Heel Height
- Sole flexibility
- Fastening style
- Longitudinal torsion
- Volume
- Variability

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Appendix 4

The Effect of Negative Heel Profile Shoes on Triceps Surae

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Introduction

❖ Eccentric exercises in the treatment of Achilles tendinopathy are the most effective conservative management.[1,2]

❖ A Review of eccentric exercise concluded that the main variance in success of such a treatment is the compliance of the patient [3]

❖ Eccentric contraction of the triceps surae occurs when the ankle is dorsiflexing, the muscle group is lengthening during this activity.[4] (Fig 1)

Ankle Range of Motion

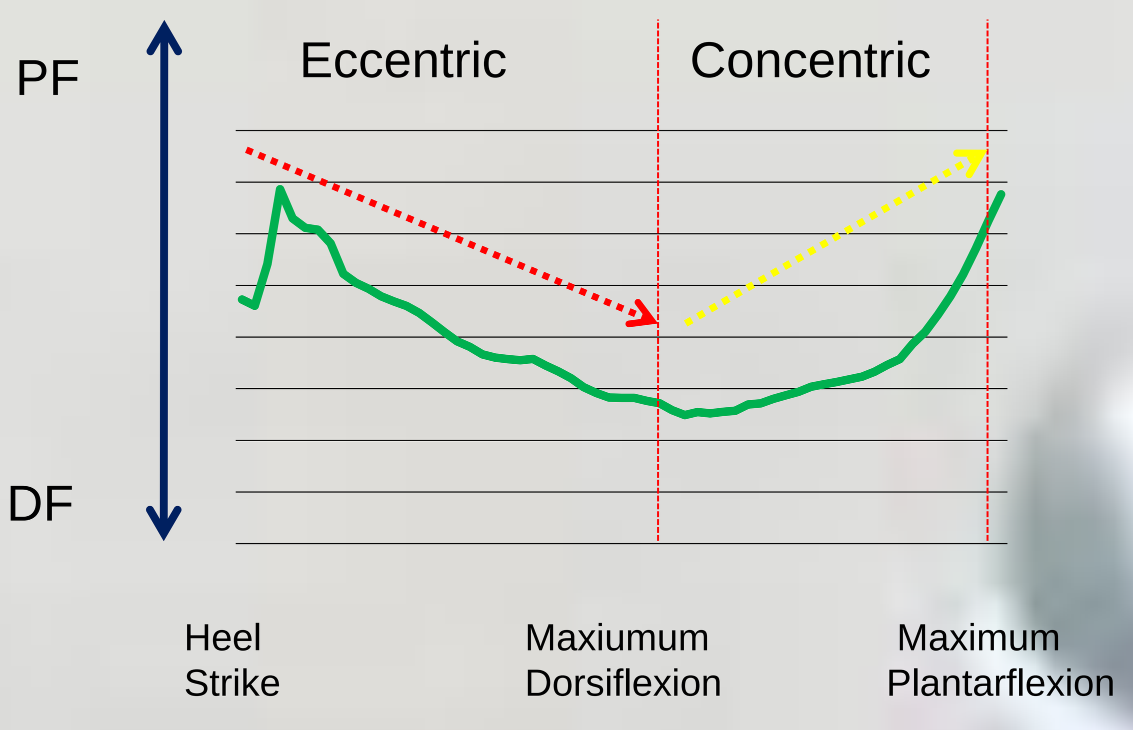

Figure 1 *Eccentric and concentric muscle contraction*

Aim of this study

❖ To conduct a pilot study to assess if negative heel profile shoes eccentrically load the triceps surae group in a similar way as the eccentric exercises issued for Achilles tendinopathy and could therefore be an alternative treatment option to improve patient compliance.

Method

❖Subjects:5 subjects
2:3 male:female,
mean age 35 years,
mean height 175cm
mean weight 70kg).

❖Equipment: EMG (TMS int. Oldenzaal, the Netherlands) sensors were placed on Triceps surae following SENIAM guidelines. Vicon Motion Analysis (Oxford UK)

❖Setup: EMG Sensors were placed on Triceps surae following SENIAM guidelines. Reflective markers were placed on the Proximal 1/3 of the tibia/lateral malleolus/Styloid process

❖Data collection: Subjects were instructed on how to perform eccentric exercise on a custom built step. (fig 2)

❖Subjects walked at a self selected speed along a 10m walk way for three conditions. 1) barefoot 2) standard plimsole 3) negative heel profile (MBT Masai GB Ltd UK) shoes.

❖Analyses: For the walking trials ankle range of motion was calculated from heel strike to maximum dorsiflexion and then maximum dorsiflexion to maximum plantarflexion.
❖Starting position for the exercise was identified as neutral and range of motion from this point to maximum dorsiflexion and then maximum plantarflexion was calculated
❖ EMG data was normalised and represents one gait cycle (heel strike to heel strike)

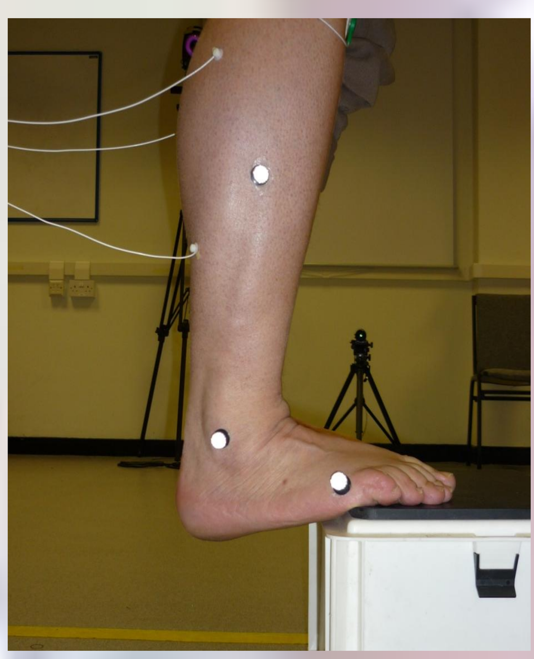

Figure 2 *Eccentric Exercise*

Results

Figure 3 indicates range of motion from heel strike to maximum dorsiflexion. Figure 4 indicates range of motion form maximum dorsiflexion to maximum plantarflexion.

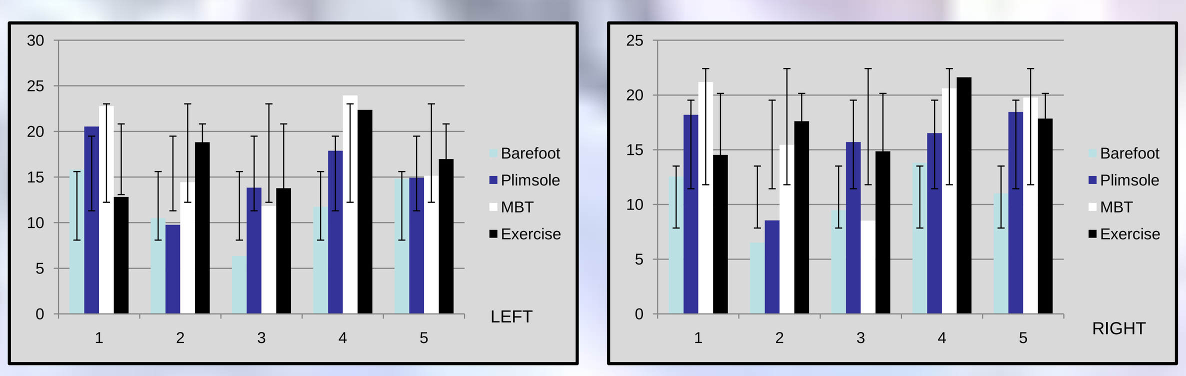

Figure 3. Dorsiflexion angle from heel strike to maximum dorsiflexion and for exercise from neutral to maximum dorsiflexion.

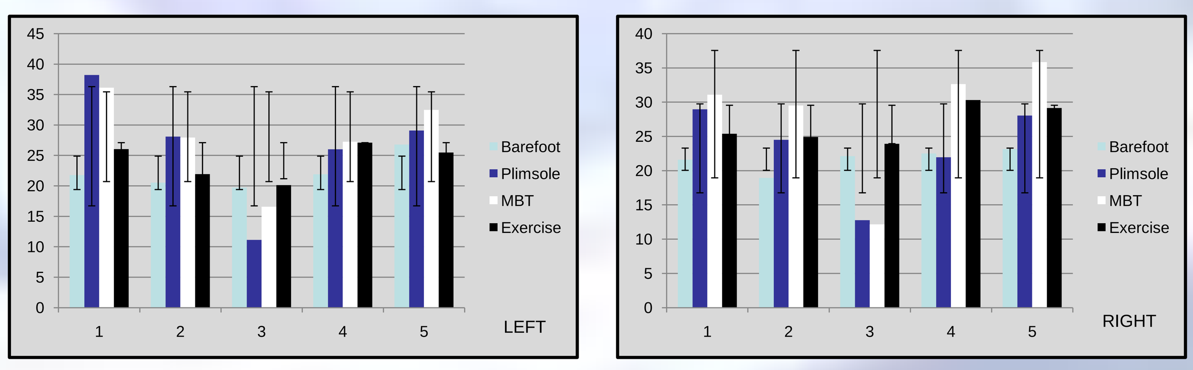

Figure 4. Plantarflexion angle from maximum dorsiflexion to maximum plantarflexion and for exercise from neutral to maximum plantarflexion.

❖Dorsiflexion from heel strike to maximum dorsiflexion increased from plimsole to MBT in 3 subjects on the left leg and 4 subjects on the right
❖Plantarflexion from maximum dorsiflexion to maximum plantarflexion increased from plimsole to MBT in subject 2 only on the left and all subjects on the right.
❖EMG Figure 5 and 6 indicated changes in triceps surae in the initial phases of gait

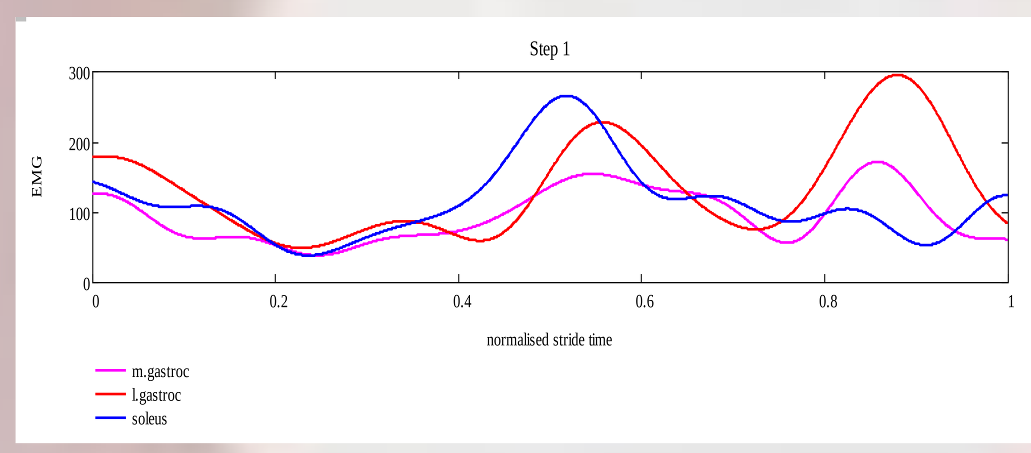

Figure 5. *EMG of Triceps Surae barefoot*

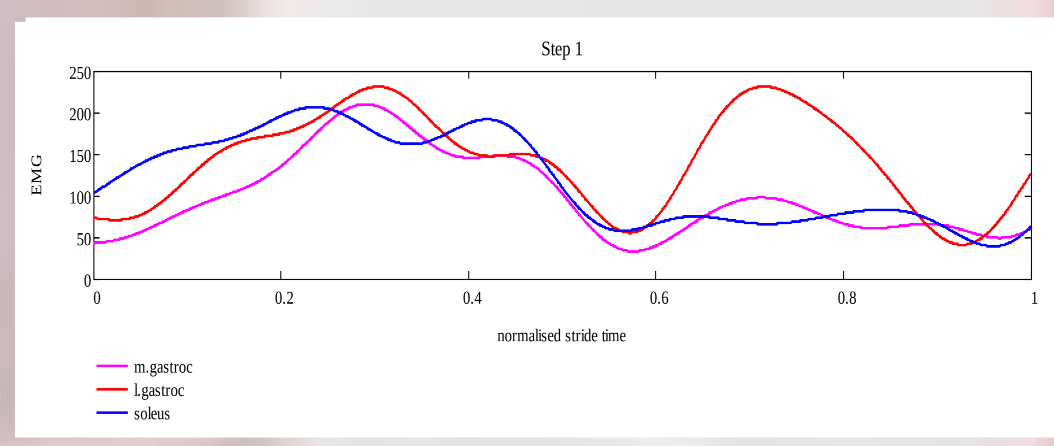

Figure 6. *EMG of Triceps Surae in negative heel profile shoes*

Discussion

❖ The use of negative heel profile footwear in the management of Achilles tendinopathy would possibly improve patient compliance and hence recovery rates from the injury.

❖ The results from this pilot study indicate that MBT negative heel profile shoes do alter ankle joint range of motion and in some subjects increase the range of motion from heel strike to maximum dorsiflexion when eccentric loading of the tendon has been shown to occur.

❖Further work, including clinical trials, would evaluate the effectiveness of negative heel profile shoes in the management of Achilles tendinopathy

Conclusion

❖ **Negative heel profile** shoes do effect the range of motion at the ankle and influence the EMG activity of the triceps surae group. Further studies for their clinical use are viable to evaluate the use of such shoes in the management of Achilles tendinopathy.

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Appendix 5

16 Footwear—The Forgotten Treatment—Clinical Role of Footwear

AQ1

Helen Branthwaite, Nachiappan Chockalingam, and Aoife Healy

CONTENTS

16.1 INTRODUCTION

Footwear in general plays an important role in protecting the foot from the environment by reducing the risks associated with trauma and enables users to have pain-free locomotion over a range of walking surfaces (McPoil 1998). However, the prolonged use of unsuitable footwear can also result in detrimental changes to occur that alter the protective nature of the shoe into a barrier between the contact surface and the natural behavior of the foot. These changes can result in altered foot morphology, reduced or impaired postural stability, neurophysiological alterations, muscle imbalance, and the development of a sensitive foot (Menz and Lord 1999, Robbins and Waked 1997). Alterations in footwear design, structure, and manufacture have been attributed to these mechanical and physiological observations.

As footwear evolves into specific subgroups, the basic structure of the shoe changes to reflect the use of the wearer. Fashion and style play a more important role as the principle use of footwear in protecting the foot changes into a color-orientated accessory (Branthwaite and Chockalingam 2009). By following this fashion pathway, the essential components required to provide stability and support are lost in the design process (McPoil 1998). These changes in behavior over the last 500 years in shoe-wearing populations have been attributed to reported footwear pathologies (Paiva de Castro et al. 2010, Rebelatto and Aurichio 2010).

The last decade, however, has seen more attention being focused on using footwear as a means of improving function, in particular running, and athletic shoes that have been developed to enhance performance. These shoes that have been designed to alter behavior can also be used as a therapeutic device. This chapter will focus on the design aspects incorporated into footwear in an attempt to improve performance or treat/prevent injuries, examine how functional shoes can change gait and pathology, and discuss some of the new concepts in footwear design.

16.2 FOOTWEAR DESIGN AND TECHNOLOGIES

Developments made along the road of technological improvements have included many functional and style modifications to alter fit, comfort, and performance within running and athletic shoes. Brand specifications have become a marketing point with enhancements including air, gel, fluid, and changes in midsole material. Companies have employed scientific researchers to test and adapt the designs to improve motion control. Certain design parameters are agreed upon as being beneficial including the heel geometry, stiffness, and heel collar (Figures 16.1 and 16.2).

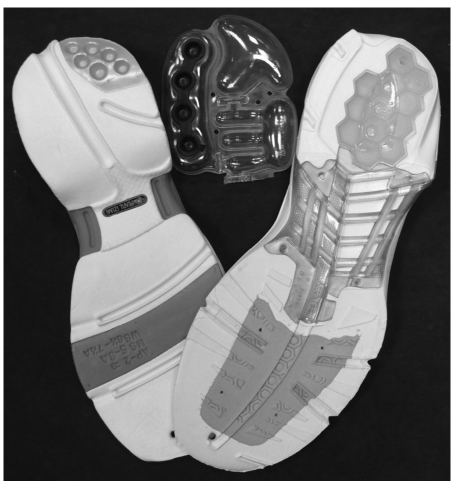

FIGURE 16.1

FIGURE 16.2

16.2.1 Heel Counter and Collar

A stiffer well-fitted heel counter has been found to reduce rearfoot motion and improve comfort (Anthony 1987, Van Gheluwe et al. 1999). Injuries associated with increased rearfoot motion include tibialis posterior dysfunction, Achilles tendonitis, and plantar fasciitis, all of which can improve when a stiff well-fitted heel counter are incorporated into footwear design. Heel collar height has been suggested as a desirable feature to prevent ankle sprains and improve postural stability. This design feature is thought to provide mechanical support around the ankle region and improve the proprioceptive feedback of the ankle position. The presence of cushioned material around the ankle region is thought to provide mechanical lateral ankle stability, such that rapid excursions of the foot into eversion or inversion are restricted by the shoe (Menz and Lord 1999, Stacoff et al. 1996). It is also thought that the presence of the high heel collar may provide additional tactile cues, thereby improving proprioceptive input to the central nervous system (CNS). Furthermore, there have been suggestions that the extrasensory feedback provided by a high collar, similar to ankle taping, ankle bracing, and knee bracing, may facilitate joint position sense and improve medio-lateral balance (Menz and Lord 1999).

16.2.2 Shoe Weight

Increases in shoe weight have been associated with oxygen consumption and performance. A lighter shoe can improve oxygen consumption by 1% for every 100 g lost in weight (Morgan et al. 1989, Williams and Cavanagh 1987). For an individual who chooses running for general exercise, this difference may not be significant to their performance; however, to the elite athlete such changes could be critical to their career. Choosing the correct footwear that supports the foot and allows for normal function as well as not weighing too much can be difficult as a reduction in weight often changes the composition of materials which correlates to a reduction in structure and support.

16.2.3 Sole and Midsole

16.2.3.1 Thickness and Density

Sole thickness and density and the type of materials used in manufacture and design also vary between brands. Dual density sole structures have been adopted in running shoes to add stability and give cushioning to the wearer in the appropriate areas of the foot. Changes in density and thickness have been shown to affect the stability and balance of the user. Shoes that are manufactured with a thicker and softer sole have been associated with increases in dynamic instability and a reduction is postural balance (Robbins et al. 1992, Sekizawa et al. 2001). Conversely, shoes that have a thinner stiffer sole improve both stability and balance parameters (Menant et al. 2008, Perry et al. 2007, Robbins and Waked 1997, Robbins et al. 1994). These design features affect afferent feedback to the CNS regarding foot position. This method of altering sole density and thickness can be utilized when there is diminished or impaired feedback; for example, in an elderly population who are at risk of falling due to altered stability and balance, a thinner-stiffened sole can improve feedback reducing falls (Robbins et al. 1992). Similarly, a softer thicker sole may help in the rehabilitation and strength conditioning of ankle instability where the shoe is used as a training device to improve feedback.

The concept of a dual density midsole has been adopted to alter the stiffness and cushioning properties of the shoe. The medial border of the sole is manufactured from a stiffer material than the midsole attempting to reduce pronation. Stacoff et al. (2000) used a dual density shoe to evaluate motion during running and found minimal changes. These results were also reported by Morio et al. (2009) who found that midsole hardness and stiffness did not affect the foot pronation during walking or running. However, Heidenfelder et al. (2006) reported benefits of using a dual density sole. Their study measured impact shock rather than assessing motion and demonstrated that the cushioning properties of the shoe are more beneficial than the motion control element. The application of such research will benefit clinicians in advising appropriate footwear for particular conditions. The prescriptive nature of footwear advice will assist in patient-specific management plans, giving individual recommendations dependent on presenting features rather than generalizing specific injuries for a specific shoe.

16.2.3.2 Sole Design

The angle and position of flexion at the forefoot of the shoe is known as the sole flex. It is important in design and manufacture because flexion at the metatarsophalangeal joints is a normal requirement for gait (Menz and Sherrington 2000). If the shoe does not flex with the natural angle of the metatarsals during the propulsive phase of gait, the shoe may either flex against the foot or direct motion and propulsion laterally causing instability. Matching footwear to the patient morphology and foot type will assist in preventing injury and discomfort from the shoe; forefoot flexion at propulsion is important to maintain stability and forward progression of the body's centre of mass (Menz and Lord 1999) (Figures 16.3 and 16.4).

Cleat design and slip resistance of the outer sole is another aspect of footwear design that is important in motion control. Football, rugby, and hockey where the

FIGURE 16.3

(a) (b)

FIGURE 16.4

cleat orientation and size are critical to provide grip have been shown to increase rotational forces around the knee joint, induce cruciate ligament injuries, and stress (Villwock et al. 2009). However, changes in the position and orientation of the cleats have not been shown to reduce the incidence of such injuries and it is thought that the cutting manoeuvres involved in such sports are more influential than the footwear. Cleat design in running shoes has had little attention although the type of activity and terrain have been identified as important considerations when looking at cleats and outsole construction (McPoil 2000).

16.2.3.3 Insert Adaptations

Other technologies incorporated into footwear design to improve or alter motion include modifications that allow for the windlass mechanism to function efficiently. This type of modification within the shoe would be particularly useful in the management of plantar fascial pain and first metatarsal phalangeal joint pathology associated with a dysfunctional windlass mechanism. Payne et al. (2005) examined whether the windless mechanism was enhanced in all shoes marketed as having windlass technology and found positive changes, but the results differed with each brand of shoe. Other trends have come and disappeared depending on the success of that shoe model: heel flare, rearfoot and forefoot valgus adaptations, cobra padding, and an arch cookie are to name but a few. The generalization of such features available to the mass market reduces specificity as the incorrect match and advice regarding shoe and foot type causing ill-fitting uncomfortable shoes. It is becoming more common for specific running and athletic shoes to be provided by retailers with advanced knowledge into the characteristic and design features available from each brand and model. Various motion analysis systems available within retailer's premises provide further detail on the gait pattern of an individual, allowing for informed judgment on the specific models, brand features, and composition of the footwear matching the recorded data.

16.2.3.4 Shock Absorption

The human body's ability to absorb shock involves several complex mechanisms, whilst running increases the load and shock that has been associated with joint disease, particularly knee pathology (Lafortune et al. 1996). Footwear modifications to enhance shock absorbency are common place and it has been suggested that these design features in running footwear must be able to provide adequate and durable cushioning systems to enable safe participation in sports (Frederick 1995). Changes in material properties and behavior provide shock absorption characteristics for the wearer in an attempt to prevent overuse injuries resulting from repetitive impact loading. It can be theorized that a thicker sole material would deform more than a thinner sole material, and thus, impact forces will be attenuated more in the thicker sole giving that shoe better shock absorption (Barnes and Smith 1994). However, studies looking at the effect of running shoes on impact forces have not been able to show a systematic difference (Aguinaldo and Mahar 2003, Cole et al. 1995).

The cushioned shoe has been developed to attenuate shock. However, research that has investigated other parameters that are altered with the introduction of shock absorbency shoes have found that impact force may not be the significant variable that is altered. Plantar pressure can be altered in cushioned shoes, yet the type of cushioning material used in the design does not affect the degree of pressure changes (Clinghan et al. 2008). Loading rates during gait and timing for each of the observed phases have also been investigated and shown to alter with the use of cushioned shock absorbency shoes (Hennig and Milani 1995, O'Leary et al. 2008).

Oxygen consumption and muscle activity have both been investigated when wearing different shock absorbency shoes. Softer, more compliant and resilient shoes required less oxygen to run in than a stiffer shoe, thus improving the rate of fatigue (Frederick 1986). However, yet again there is the literature which contradicts this with Nigg et al. (2003) finding that a visco-elastic heel and an elastic heel did not affect oxygen consumption or alter muscle activity. Although, some individuals showed systematic and consistent differences in the heel material properties. Nigg (2001) also suggested that impact forces during normal physical activity are important because rather than being a direct cause of potential injuries, they affect muscular work; therefore, attenuating those impacts could result in a change in muscular function.

When the human body senses it is being exposed to larger impact shocks due to large high frequency ground reaction force components acting through the plantar region of the foot, it has been shown that the human body will adapt its running style (De Wit et al. 2000, Lafortune et al. 1996). Furthermore, various studies have identified that by purposefully adapting the running style of participants, the loading characteristics can be significantly changed (Laughton et al. 2003, Lieberman et al. 2010, Oakley and Pratt 1988).

16.2.3.5 Material Properties

The midsoles of running shoes are typically made from ethylene vinyl acetate (EVA) and/or polyurethane by varying density. While research has found that midsole hardness had little or no effect on lower extremity muscle activity, impact peak, and ankle joint forces, it has been shown to effect rearfoot movements during touchdown and muscle forces on the medial side of the subtalar joint (Nigg and Gérin-Lajoie 2011, Stacoff et al. 1988). One important aspect of the materials used in running shoes is their durability with research suggesting that running shoe age can contribute to injuries (Taunton et al. 2003). Verdejo and Mills (2004a) examined the durability of EVA foam running shoe midsoles with their results showing a 100% increase in peak plantar pressure after 500 km run and structural damage of the foam after 750 km run. They related the decrease in the cushioning properties to a decrease in the initial compressive collapse stress and not to a change in the air content (Verdejo and Mills 2004b). Furthermore, research carried out by Cooket al. (1985) found a reduction in shock absorption of running shoes with increased mileage. Compression forces applied to the outer sole material whilst running can affect the cushioning properties by up to 30% (Kenoshita and Bates 1996). Similarly, it has been shown that EVA can take up to 24 h to return to its original state, and therefore, people who use running shoes more than once in a day should think about the changes in the materials and how that may impact on cushioning and potentially increase the risk of injury occurrence (McPoil 2000). This evidence supports the thought that a running shoe with an EVA sole should only be used to run with for a set distance and after that the material properties change and could enhance injuries related to shock absorbency.

16.2.3.6 Other Design Aspects

Innovation and concept shoes have given inspiration to changing the mould for manufacture of the running shoe. The designs and theories have focused on being prophylactic in nature by providing a better performance for the wearer and a reduction in the incidence of injury. For example, Heeless technology™—this shoe development began from the experience of a marathon runner who was plagued by Achilles tendon injuries. The design attempts to alter foot strike pattern and the loading pattern on the Achilles tendon. Similar innovations include the Hoka™ One One shoe which is based on a rocker shoe concept but aims to increase the contact surface area of the shoe with the floor. The aim of this concept appears to help improve stability and users gain the benefit of the additional volume of the shoe.

The volume of the forefoot of a shoe has been indicated to be significant in the development of foot pathology (Paiva de Castro et al. 2010, Rebelatto and Aurichio 2010). Increasing the volume of the forefoot allows for the metatarsals to function without medial and lateral compression and therefore reduces the instability and impingement pathologies commonly seen in the forefoot. The use of shoes with increased volume and stability could be used in sufferers of forefoot pathology. As well as users of shoes that alter loading patterns of the Achilles can alleviate strain around potential injury sites. It is essential to be advised as to which shoe would suit the wearer's foot type and mechanics as adverse effects may be encountered from the use of concept shoes.

16.2.4 Comfort

Oxygen consumption and therefore fatigue have been strongly correlated with comfort. Research by Luo et al. (2009) found that the participants who were most comfortable had a significant decrease in oxygen consumption. If a shoe is making the user consume more oxygen and the muscle activity is higher, then it is understandable that the user will feel uncomfortable in that shoe. Comfort has been used as a predictive factor for muscle activity and intensity in the lower limb (Mundermann et al. 2003). Improving comfort of a shoe can result in a reduction in stress-related injuries (Mundermann et al. 2001). If a shoe is comfortable and fits well, it is less likely to be compressing the foot in any way. Forefoot width and depth have been shown to be positively correlated to foot pain and pathology. The narrower and shallower the shoe, the higher the incidence of forefoot injury (Paiva de Castro et al. 2010, Rebelatto and Aurichio 2010). The breadth of the forefoot can influence the perception of comfort and any compressive forces around the forefoot altering the structure increase localized stress on the metatarsals (Morio et al. 2009). However, Miller et al. (2000) found that the fit of the shoe is not solely sufficient for comfort. They found that skeletal alignment, shoe torsional stiffness, and cushioning seem to be mechanical variables which may be important for comfort. Comfort has been correlated with a number of measures and differences in comfort have been associated with changes in kinetics, kinematics, muscle activity, foot shape, fit between foot and footwear, skeletal alignment, foot sensitivity, weight of the shoe, temperature, and joint range of motion (Mundermann et al. 2003, Wegener et al. 2008).

Most people are able to identify what is a comfortable and noncomfortable shoe. This measure therefore can be adopted in the assessment of footwear fitting and give confidence to the person giving advice about which shoe to wear that if the shoe is perceived as comfortable then there is a reduced chance of developing injury.

Adaptation and individual variability can be used to describe why studies investigating the outcomes of footwear modifications do not generate systematic differences. As individuals, the human body responds in many different ways to intervention. This has been shown in several studies around shock absorption and impact forces where the conclusions derived from the work have been that outcomes vary according to the individual and therefore cannot be generalized (Frederick 1986, Kersting et al. 2006, Nigg 2001, Nigg and Wakeling 2001). Translating this information into an injured population will possibly give the same results. One patient group may respond well to a shock absorption shoe when they have developed plantar fasciitis, whereas others may not get any relief from wearing a cushioned shoe.

16.2.5 Neutral Shoe

The original running shoe design did not have the characteristics of support along the medial side of the shoe and the dual density midsole; these motion control features were added later in the development based on the research of the time. The basic model of a running shoe is still manufactured today and provides the consumer with a shoe that is known as being neutral. This shoe may be preferred by orthoses users as the last used within the manufacturing process and the resulting structure provides a base to add a specific orthotic prescription to (Baker et al. 2007). Neutral shoes have been shown to reduce the muscle activity in tibialis anterior and soleus compared to motion control or cushioning shoes (O'Conner and Hamill 2004) providing positive enhancement for a neutral shoe to be included in a management plan for overuse disorders of these muscle groups. However, Cheung and Ng (2007) compared the effects of motion control and neutral shoes on muscle fatigue and found that the motion control shoe was superior in minimizing muscle fatigue. Fatigue has been identified as a strong link in the development of overuse injuries with increases in metatarsal loading and impact accelerations being observed in exhausted subjects (Mizrahi et al. 2000, Nagel et al. 2008). Footwear that can improve the fatigue rate of users is desirable to use as the impact on injury occurrence may be beneficial.

16.3 OVERUSE INJURIES

While previous physical activity would seem to predispose individuals to develop a musculoskeletal system that was less likely to suffer an overuse injury due to conditioning, research has suggested this may not be the case. No correlation was found between army recruits who participated in sporting activities prior to training and those who did not with the occurrence of stress fractures (Swissa et al. 1989). Studies such as this have to be approached with caution as a participant who is physically fitter than another may have increased their body's ability to withstand larger forces leading to stress fractures. However, due to this, the participant may expose their body to more intense exercise over a longer duration. In many studies, this may be a problem that affects the findings. If an athlete is more physically fit and more protected from injury due to previous training, this may lead them to expose their body to more intense exercise and more volatile movement strategies.

It would appear that getting the balance between enough exposures to lower extremity impacts to promote health in the musculoskeletal system without reaching the point of injury may be the correct way to avoid stress fractures. However, controlling an athlete's movement characteristics strictly is not necessarily possible and thus dictates the stresses to which their body is subjected in a competitive environment (Ekenman et al. 2001). Using army recruits who undergo controlled physical activity provides sports scientists with large amounts of comparable data. Using army recruits (n = 1357), research has found that a week's rest in the middle of an 8 week training course did not significantly reduce the incidence of overuse lower extremity injuries (Popovich et al. 2000). The results of this relatively large study of army recruits found that the lowest injury group was the one who ran the most miles with intermittent rests, recommending running and marching with single day of rest in between as having a positive effect on lower extremity overuse injuries such as stress fractures.

16.4 NEW CONCEPTS

The trend and focus on the development of sports footwear has been to provide a shoe that makes the body exercise muscles and provide a workout within the normal working day. Other more specialized running shoes have focused on increasing or improving performance.

16.4.1 Instability Shoe

The concept of introducing a rocker sole to footwear has been used within orthopedic and rehabilitation medicine for centuries with a specific aim to off-load compression forces from joints within the lower limb (Bauman et al. 1963). More recently, the therapeutic intervention of improving stability by exercising the systems that provide locomotive stability has been adopted into the footwear industry. The MBT® shoe was the first commercial instability shoe to affect the mass market.

MBT training shoes have been associated with variable changes between subjects due to different strategies for compensation being employed (Nigg et al. 2006, Stewart et al. 2007). The marketed aim of the MBT, unstable shoe, has been to provide an exercise workout whilst walking in the shoe. However, it is not clear from research to date as to the specific effects of the shoe on lower limb function. Landry et al. (2010) used an EMG circumferential linear array with MRI scanning to evaluate the activity of the extrinsic foot muscles whilst standing in the MBT shoe. As with previous studies, the anterior and posterior sway increased in the MBT shoe (Nigg et al. 2006, 2010). However, the activity of the soleus muscle remained unchanged. There was increase in activity in the anterior leg compartment and peroneal muscle group, suggesting that these muscles are recruited as a method to improve stability whilst wearing the shoe.

The APOS shoe has a similar strategy of creating instability for the user, unlike the MBT—the instability comes from a medial and lateral direction and can be altered to balance loads. The use of this shoe has been shown to be effective in the management of knee osteoarthritis where subjects showed a 70% improvement in pain over a 8 week period which were sustained after 1 year (Bar-Ziv et al. 2007). Elbaz et al. (2010) support the conclusion and the use of the shoe is advocated in the management of knee osteoarthritis. Patient selection and correct management with the specific shoe will be critical to recovery with reports of limitations in the use of the footwear and patient compliance. However, Reeboks launch of the Tone ups® provide a commercially available product that mimics the more prescriptive APOS shoe. Independent research evaluating the effect of the Tone ups has yet to be completed.

16.4.2 Gender

Although there is a clear need for distinguishing footwear between genders as previous research has reported that females have higher-arched feet and a shorter outside foot length (Wunderlich and Cavanagh 2001), yet in general running shoes are manufactured for unisex populations. During standing results, a significant difference ($P < 0.05$) in plantar contact areas was reported, when comparing genders suggesting different requirements from a sports shoe (Gravante et al. 2003). Changes in the manufacture and design of female-specific running shoes will help with fit and comfort for the female runner (Krauss et al. 2010). The changes in fit are not the only differences between male and female. Ferber et al. (2003) highlighted that lower extremity movement patterns are more diverse in women than men. Female changes and requirements and studies comparing mixed gender samples should consider this in any evaluation of results.

It has also been reported that footwear size selection in female populations tend toward choosing footwear that is designed for smaller feet which has been shown to be linked to injury occurrence (Frey et al. 1995). Shoe manufacturers construct slender shoes for females compared to males to allow for the more slender anatomy of the female foot. However, research has found that although the female-specific shoes were reported to have provided a better fit by the female participants, the shoes did not improve the cushioning or rearfoot control characteristics during running (Hennig 2001). Overall, gender-specific footwear seems sensible considering the differences reported in plantar regions and foot size. One of the major footwear brands has gone on to develop some gender-specific features within their footwear range based on published research (Bryant et al. 2008). These include varied shock absorption capability within midsoles of running shoes and special support mechanisms which are altered to provide support for changes in arch height over a 28 day ovulation cycle. Furthermore, as research indicates that Achilles tendonitis is more prevalent amongst female runners, some of the footwear design has a higher heel gradient on running shoes for women, which relieves much of the loading that causes Achilles tension.

16.5 FUTURE DEVELOPMENT

Over the years, preventing overuse injuries has been the focus for footwear scientists and designers. This is an area which still needs a variety of sport-specific or event-specific prospective studies. This should include how previous training, duration, and intensity of activities can be adapted along with specific footwear to reduce the risk of overuse injuries.

QUESTIONS

16.1 How have technology enhanced strategies that influence design impacted on lower limb injuries?
16.2 What other design features have been incorporated into footwear design to improve function and reduce onset of pathology?
16.3 How do shock absorbency and comfort effect fatigue and overuse injury?
16.4 Instability shoes have been shown to alter postural stability, how could these shoes be used to improve stability in those who are unstable?
16.5 How can footwear design improve the female runner's experience?

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Appendix 6

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Function of the triceps surae muscle group in low and high arched feet: An exploratory study

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ABSTRACT

The Achilles tendon has been shown to be comprised of segmental components of tendon arising from the tricpes surae muscle group. Motion of the foot joints in low and high arched feet may induce a change in behaviour of the triceps surae muscle group due to altered strain on the tendon.

Surface electromyogram of the medial and lateral gastrocnemius and the soleus muscle from 12 subjects (with 6 low arched and 6 high arched feet) (1:1) was recorded whilst walking at a self selected speed along a 10 m walkway.

The results showed a high variability in muscle activity between groups with patterns emerging within groups. Soleus was more active in 50% of the low arch feet at forefoot loading and there was a crescendo of activity towards heel lift in 58% of all subjects. This observed variability between groups and foot types emphasises the need for further work on individual anatomical variation and foot function to help in the understanding and management of Achilles tendon pathologies and triceps surae dysfunction.

1. Introduction

The triceps surae muscle group comprising of the soleus, medial gastrocnemius and lateral gastrocnemius insert into the calcaneus via a common Achilles tendon. It has been reported that the tendons arising from these muscles twist so that the insertion forms a precise pattern. The fibres that insert on to the posterior aspect of the calcaneus originate from the medial head of gastrocnemius with the lateral section of this muscle feeding into the posterior lateral border of the tendon. Lateral gastrocnemius forms the anterior/deep part of the tendon with the fascicles of soleus occupying a central medial position (Fig. 1) [10]. Furthermore, anatomy and structure of the Achilles tendon has been reported as variable between subject groups with differences in proportion of triceps surae composition at the site for insertion [8].

The primary function of the triceps surae around the ankle complex is noted as a plantarflexor of the foot on the leg but it is acknowledged that it does contribute to other movements including inversion and eversion of the subtalar joint [7]. Whilst, soleus appears to primarily control the movement around the ankle joint, both heads of gastrocnemius behave as a stabiliser of the ankle but the primary action of gastrocnemuis is flexion of the knee [11]. At the subtalar joint, lateral head of gastrocnemius always contributes to eversion of the subtalar joint at all angles with a reported optimum moment arm occurring when the ankle was set at 20° dorsiflexion. The medial head provides a small inversion moment arm only when the foot is everted, this increases when the ankle is again dorsiflexed at 20° [1].

The exact function of the triceps surae is important when considering anatomical differences between subject groups. The individual shape of the calcaneus and talus, influences the motion that occurs around the subtalar joint. Changes in motion around the subtalar joint could lead to changes in the tensile load on the Achilles tendon if the axis lies medially then the foot would pronate (low arch) and there could be an increase in tensile load on the medial portion of the Achilles tendon conversely if the axis lies laterally then the foot supinates (high arch) and the increased load and tension alters to the lateral portion of the Achilles tendon. This change in tension and load could alter the behaviour of the triceps surae group dependant on the foot position (Fig. 2). The individual characterisation of a foot type can be assessed in many ways. Most recently the Foot Posture Index (FPI) has provided a multifaceted approach to evaluating foot shape [2]. This index is commonly used in research and clinical practice and categorises the foot into high arch, normal or low arch. Other methods of foot type characterisation fail to address the foot in a multidimensional way and only provide a category based on restricted observation [3,4].

The aim of this study was to identify if the triceps surae group functions differently in high and low arched feet considering the reported variations in structure and the composition of the Achilles

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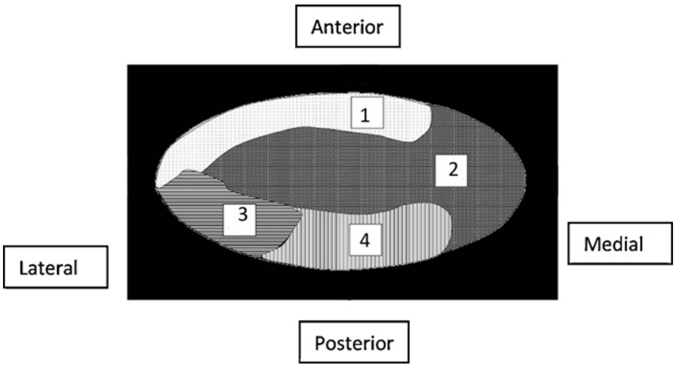


Fig. 1. Transection of the Achilles tendon 1 cm above the insertion of the calcaneus, (1) the lateral head of gastrocnemius; (2) soleus; (3) the fibres from the lateral part of the medial head gastrocnemius and (4) fibres from the medial portion of the medial head of gastrocnemius.

Adapted from Szaroa et al. [10].

tendon in relation to the medial and lateral heads of gastrocnemius as well as soleus. Identification of variation will enhance clinical practice in the management of Achilles pathologies and observation foot type classification in future research.

2. Materials and methods

A cross sectional study design using convenience sampling was employed. Ethical approval and consent were obtained to partake in the study prior to testing beginning (1:2).

The subjects who met the following inclusion criteria were invited to participate in the trials.

- 18–50 years of age males.
- Achilles tendon and triceps surae injury free for 6 months (2:2) with no previous surgery.
- FPI of above 6 or below 0 [2].
- High or low subtalar joint axis [4].

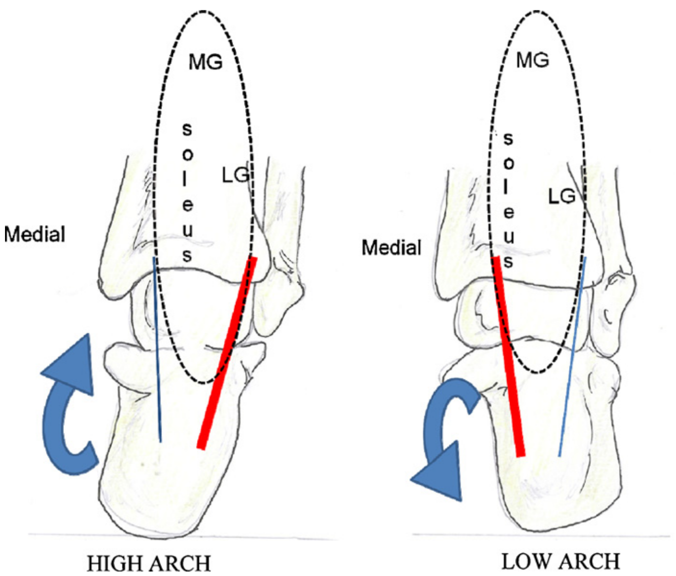


Fig. 2. A high arch foot with inversion of the calcaneus increases strain on the lateral border of the Achilles resulting in a supinatory moment to occur. A low arch foot with calcaneal eversion increases strain on the medial portion of the Achilles tendon, inducing a pronatory moment.

A set of monopolar electrodes was placed in accordance to SENIAM guidelines [5] on the medial and lateral head of gastrocnemius as well as on the soleus muscle. The tibial tuberosity was used as a non-active point to place the earth electrode. Standard foot switches were placed on the calcaneus and the apex of the first digit to determine gait cycle events. An telemetry electromyography system (Portilab, TMSi, Enschede, The Netherlands), sampling at 2048 Hz with a HighPass cut off frequency of 7, was employed to collect the data. The processed data was subjected to further analysis in MathCAD (Version 15: PTC, MA, USA) (1:3).

The subjects were instructed to walk barefoot at a self selected speed along a 10 m walkway. Once, the subjects were accustomed to the lab environment, data was collected from 3 walking trials. On completion of walking trials, the subjects were directed to perform a maximum dorsiflexion and plantarflexion in a static position. This data was then used as a baseline for analysing muscle function in walking trials. Analysis of the EMG data synthesised a mean value for each muscle. The mean electrical activity of the gastrocnemius (lateral and medial heads combined) was subtracted from the mean activity of soleus muscle. This demonstrated the difference in behaviour between the muscles.

3. Results

12 male subjects (mean age 37 SD ± 5 years) were identified as having either a high or low arch profile [2,4]. 6 subjects were classified as having a low arch and 6 high arch.

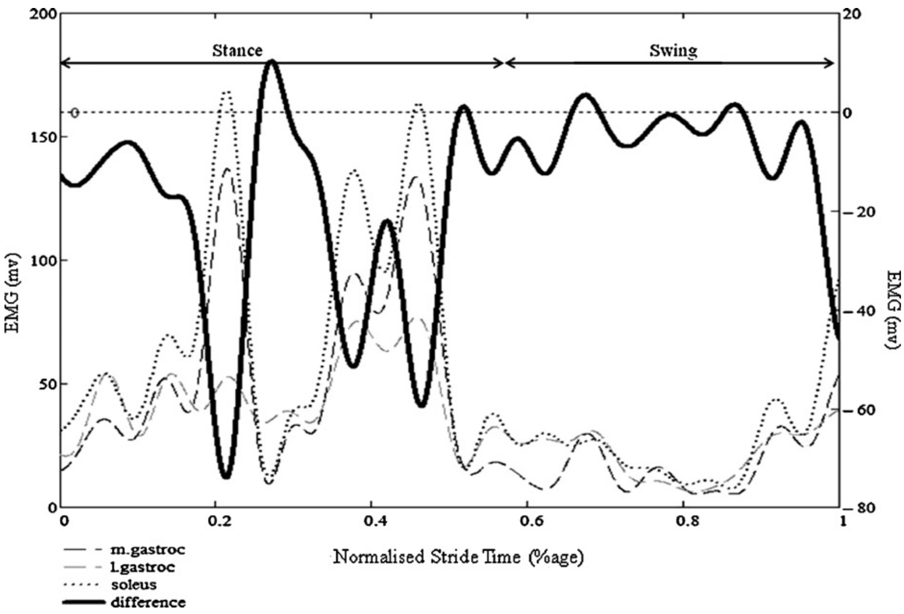
EMG data showed great variability between subjects with unpredictable activity in the muscles tested. In 3 of the low arch subjects a double spike of activity was seen, the initial spike occurred at forefoot loading (20% of gait cycle) and second spike at heel lift (40% of gait cycle)(Graph 1). This pattern was not seen across the subjects in the high arch group. From all the subjects, 7 demonstrated a crescendo of activity of the soleus muscle, from forefoot loading (20% of gait) peaking at heel lift (40% of gait cycle).

Swing phase activity also showed behavioural difference between the means of gastrocnemius and soleus. 4 of 6 in the high arched feet showed no difference between the muscle activities and 4 of 6 in the low arch group showed great variability between the differences in activity of gastrocnemius compared to soleus (Graph 2).

4. Discussion

The primary aim of this paper was to examine if the triceps surae group behaved in a different way in two extremes of foot type. The initial results show some interesting trends suggesting that the muscles assessed do behave in a different way between individuals although no precise differences could be identified between the two defined groups.

A low arched foot presents with an everted position of the calcaneus rotating the subtalar joint into a pronated position. The composition of the Achilles tendon indicates that the medial and central portion originates from the fibres of the soleus muscle, therefore in a low arched foot that rotates towards the medial border, these fibres could be placed under greater strain altering the behaviour of the muscle. The results from this study show that in 50% of the low arched feet the soleus muscle worked harder, particularly at forefoot loading where there was an extreme difference in activity between soleus and gastrocnemius. The altered behaviour and increased activity of the soleus could be associated to the composition and location of the Achilles tendon at the insertion and the strain applied whilst the foot is pronated. Individual variability of tendon composition could describe why increased activity was only seen in half of the subjects.

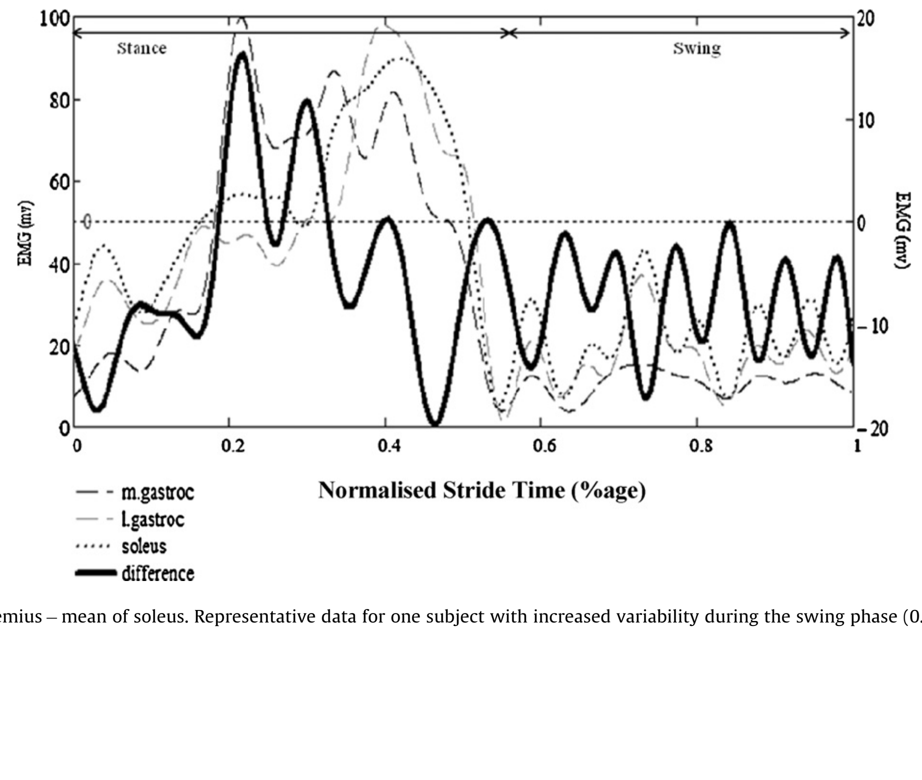


Graph 1. Mean of gastrocnemius – mean of soleus EMG. Representative data for one subject with a low arch, from heel strike to heel strike.

Anatomical variation could lead to changes in the moment arms and relative changes in the resting stiffness of the structures about the joint. It is claimed that the anatomical variability can be quantified using simple clinical scales which are used in the assessment and treatment of foot pathology. The Foot Posture Index is one common scale used in clinical practice and although assessment using this index can generate two feet with the same score the 6 faceted index could mean that each individual has rotation or functional changes at different parts of the foot. The subjects recruited in this project were assessed by FPI and grouped accordingly, however individual scores for each of the 6 areas within FPI were not able to be matched and could account for the increase in variance seen between subjects in the same group. Further work should match foot types to each of the 6 criteria within the generated FPI to provide a more rigorous assessment of the posture characteristics.

Furthermore, the variable pattern of triceps surae muscle activity reported during stance phase demonstrates the variability in employing different methods of muscle recruitment within subjects during gait. The importance of understanding these variable patterns could been essential to enhance clinical practice in the management of Achilles tendon pathologies and other dysfunction associated with triceps surae. Achilles tendon pathology has been reported as a difficult presentation to manage with eccentric loading exercises deemed as the most successful treatment modality [6,9]. However, this treatment has not been successful in all cases. By investigating further into the specific function of the triceps surae muscle group associated to anatomical variance a through understanding of how an individual triceps surae muscle works will lead to a more specific exercise regime being employed.

The subjects recruited for this study had no known Achilles tendon or triceps surae injury at the point of testing. Investigation into the differences and adaptability of a pathological sample with high and low arched feet would also enhance the understanding of the function and use of the triceps surae muscle during gait. As the



Graph 2. Mean of gastrocnemius – mean of soleus. Representative data for one subject with increased variability during the swing phase (0.6–1) from heel strike to heel strike.

subjects included in this study were healthy normal's the results highlight (1:4) great variability with patterns of activity being seen within and outside of the groups created a pathological group may demonstrate more uniform patterns of activity related to the specific pathology.

The observations made in this paper demonstrate that muscles may work in a different way depending on underlying skeletal structure and joint rotations. Continuation of this work will strengthen the arguments presented and help in the understanding of variability and the impact this has on clinical management of presenting pathology as well as support the discussion and interpretation of research outcomes when studying foot and lower limb function.

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Appendix 7

Article

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Footwear choices made by young women and their potential impact on foot health

Helen Branthwaite, Nachiappan Chockalingam, Sarah Grogan and Marc Jones

Abstract

Modern footwear has been associated with the development of foot pain and pathology in the ageing adult. Yet this foot health issue does not seem to alter the footwear purchases made by younger women. In total, 162 teenage girls were questioned regarding shoes purchased over a 6-month period. The results indicated that footwear choices are activity specific and participants chose the style and design of shoes related to the image they wanted to portray. Association of footwear choice to foot function and health was not found to influence choice of footwear.

Keywords

appearance, body image, emotions, females, health behaviour

Women are more likely to present with foot pain when compared to men, and it is suggested that choosing footwear is based on fashion rather than comfort and this may be a primary reason for foot pain (Burns et al., 2002; Hill et al., 2008). The long-term effects of wearing inappropriate fashion footwear can lead to foot joint deformities and associated pain causing an increased impact on health costs and disabilities in the older adult. Various categories of inappropriate footwear that are directly correlated to pain and pathology have previously been identified. These include (1) high-heeled shoes, (2) slip on pumps and (3) slippers (Dufour et al., 2009). These shoes when fitted incorrectly, either being too tight or loose, have also been associated with painful digits and generalized foot pain (Mickle et al., 2011). Footwear shape and dimensions have been shown to play an important role in the development of pain and deformity with a decreased volume of the shoe positively correlating to foot pain with an estimated 70 per cent of elderly females wearing shoes too narrow for the foot width (Chantelau and Gede, 2002; Menz and Morris, 2005; Paiva de Castro et al., 2010).

Outfit choice is considered to be the most significant factors when footwear selection is made by female rheumatoid arthritis population

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(Goodacre and Candy, 2011). People suffering from rheumatoid arthritis commonly are issued orthopaedic footwear to accommodate painful foot deformities. However, a recent study has shown that when given a choice, only 5 per cent of the participants choose to wear the prescribed footwear. Being faced with wearing unattractive shoes that assist in reducing pain, most participants would prefer to comply with fashion (Silvester et al., 2011). The restriction in choice and appearance of orthopaedic footwear design has a direct impact on the self-esteem and body image in patients who wear the shoes (Firth et al., 2011).

This strong correlation between inappropriate and ill-fitting footwear and poor foot health in the ageing population should alert younger generations to be cautious regarding the shoes chosen particularly as footwear habits during a lifespan can be influential to the onset of pain later in life (Dufour et al., 2009). However, the current trends indicate that the younger population chooses footwear depending on the current fashion rather than fit and function.

Fashion and brands are made attractive and credible to the teenage markets by celebrity endorsement (Temperley and Tangen, 2006). Widespread global phenomena can be linked to popular fashion icons and high-profile personalities. The Ugg® boot being an example, designed initially as a slipper for surfers in Western Australia, the adoption of the boot by Hollywood celebrities soon became a fashion essential (Kuksov and Wang, 2011). It has been reported in the global media that medical practitioners have found an association between foot pain and prolonged use of ‘Ugg’ style boots (Stahl, 2011). This link has yet to be scientifically investigated; however, the boot and the Ugg brand continue to grow. The evolution of a simple warm sheepskin boot has developed into a global brand phenomenon demonstrating how style and image can dominate the younger generations’ choices over the potential physical damage that may occur.

There is, however, a strong scientific link between the development of lower limb pathology and back pain while wearing high-heeled shoes (Lee et al., 2001; Linder and Saltzman, 1998; Mandato and Nester, 1999). Changes in spinal and pelvic motion over a prolonged period as well as increases in plantar foot pressure due to the alteration in the height of the heel have been directly linked to the onset of pain and pathology (Cernekova and Hlavacek, 2008; Cowley et al., 2009). Yet the fashion industry continues to design high heels despite the known association with pain and pathology to promote elegance, style, femininity, power and sexuality (Yorkston et al., 2010).

It is clear that footwear choice has an important role to play in identity, self-awareness and body image of an individual. However, the style and design characteristics of the shoe may play a more significant role in long-term foot health. There appears to be limited research around the role footwear plays in the body image of teenage individuals and what factors are involved in making footwear choices that may be healthy or unhealthy.

The primary aim of this study was to assess what footwear choices teenage girls made while purchasing shoes over a 6-month period, with the following secondary aims:

1. To investigate the relationship between the fitting and shoe size and
2. To explore in what way footwear preferences influenced the purchases made.

Method

Participants

Head teachers from sixth-form colleges within the West Midlands, United Kingdom were approached inviting students into the study. Ethical approval was granted through the University Ethics Committee and ethical practice was adhered to throughout the study. In total, 162 females were recruited from the three sixth-form colleges with a mean age of 17 years, mean mass of 56.82 kg (standard deviation (SD) ± 8.48) and a mean height of 163.95 cm (SD ± 7.61). Prior to consenting to the study, participants were given information and the opportunity to ask questions. The study was conducted over a winter period and choices of footwear were reflective of the season.

Questionnaire

The questionnaire was designed and adapted from previous validated studies (Branthwaite and Chockalingam, 2009; Jones et al., 2005) to capture the thoughts and emotions of footwear bought over a previous 6-month period. Data were collected from one session and repeat testing was not completed. The questions included open-ended and closed-ended questions around footwear purchased in the 6-month period and the choices made when purchasing the footwear. The questionnaire incorporated demographic information including measurement of foot length and width as well as details about emotional responses to how footwear choices influenced feelings. The design of the questionnaire allowed for the following themes to be investigated.

Size of shoe. Data were collected on the current shoe size that each participant wore with further information about fitting and measuring of the foot that was undertaken before purchasing the shoe. To consider any changes in behaviour, participants were also asked if sizing changed when making a purchase of a new shoe and what factors influenced the alteration in size. Data were collected for the length of the foot measured on the plantar surface of the foot to the apex of the longest toe and the width or girth of the foot measuring the circumference of the foot starting at the first metatarsal joint. Alterations in footwear sizing correlated to actual foot width, as well as inappropriate dimension and fitting have previously been significantly identified as pivotal in the development of foot pathologies (Mickle et al., 2011; Paiva de Castro et al., 2010).

Type of shoe. Images of eight different shoe designs were included for participants to identify the type of shoe that was purchased within the previous 6-month period (Figure 1). Shoe styles were chosen for varying features, including toe box shape, heel height, fastening, athletic footwear and current style. The shoes included were identified as the general styles currently marketed in footwear high street stores around the United Kingdom by evaluating the trends promoted as new stock.

Participants were also asked to identify how many pairs of shoes had been purchased, what was the reason for purchasing that specific shoe and how often it was worn over the previous 6-month period. This information was collected to indicate for how long the chosen shoe was being worn for and for what purpose the shoe had been purchased.

Choice of shoe. Participants were then asked to identify one shoe from Figure 1. This shoe was then the focus of a number of questions associated with identity and how that particular shoe made them feel using a numerical rating scale 0–4, with 0 representing no feeling towards the emotion and 4 representing extreme agreement for that emotion. The emotions investigated ranged from a spectrum of negative (embarrassed, sad, self-conscious, disappointed and dejected) and positive (content, happy, proud and cheerful) emotions.

The final section of the questionnaire focused on the importance of the following 10 factors when purchasing the chosen shoe (participants scored each factor 0–5, 0 being poor and 5 being excellent):

1. Comfort
2. Fit
3. Value
4. Support
5. Cushioning
6. Colour
7. Brand
8. Fashion
9. Heel size
10. Activity

Figure 1. Footwear styles 1–8 used to classify the type of shoe purchased within the previous 6-month period.

Participants were also asked to rate a generalized feel-good factor as a measure of self-esteem and identify other factors that had not been listed that were felt important when purchasing the chosen shoe.

Data analysis

The shoe styles shown in Figure 1 were categorized into the following three groups:

1. Flat shoes – low-heel profile with or without fastening
2. Heeled shoes – medium to high-heel profile
3. Casual shoes – trainer and boot style with generous width and low heel

Data were categorized into these three groups and were statistically analysed further using SPSS (v19, IBM). Left and right foot measurement data were assessed for multicollinearity. Sequential regression was used to predict the shoe size based on the foot length and width measured. Cochran's *Q* test was used to identify the main purpose for wearing the shoes in each shoe group; analysis was performed to identify which shoe was chosen for school, occasions, comfort, fashion, warmth and height. A Kruskal–Wallis test was performed to analyse the significant emotional factors influencing the purchase of the chosen shoe and a further Mann–Whitney *U* test was used to assess where the variance between the three shoe groups lay.

Results

Size of shoe

Of the participants, 98 per cent (n = 158) did not have the foot measured prior to purchasing

Table 1. Frequencies of stated reasons for shoe choices

Stated reasons	Shoe type					
	1 (flat), *n* = 45		2 (heels), *n* = 38		3 (casual), *n* = 31	
	Not chosen	Chosen	Not chosen	Chosen	Not chosen	Chosen
School	39	6	8	30	29	2
Occasion	45	0	35	3	8	23
Comfort	14	31	36	2	22	9
Taller	45	0	30	8	31	0
Warmth	35	10	38	0	31	0
Fashion	29	16	23	15	20	11

shoes and 83 per cent ($n = 135$) changed the size of the shoe for improved comfort (36%, $n = 59$), fit (35%, $n = 57$), to prevent slipping (3%, $n = 4$) and different sizes of feet (3%, $n = 4$). Of the participants, 23 per cent ($n = 28$) who changed the size of the shoes made no comment as to why that choice had been made. Sequential regression was used to assess the ability of a known shoe size to predict the foot width and length. Evaluation of the regression model (foot length and width) including the sequential regression Mastery Scale and Perceived Control of Internal States Scale (PCOISS) showed a total variance of the model as 81.6 per cent ($F = 0.872$; $p = 0.001$; R^2 change = 0.005). Analysis of variance (ANOVA) to investigate where the significance in the model lay indicated that the overall model was significant ($p = 0.005$), with left foot length being individually significant ($p < 0.003$).

Preference of shoe type

Over a 6-month period, a total of 458 pairs of shoes were purchased – 134 pairs of type 1 (flat shoes) were purchased; from this total, 126 of those shoes were ballet shoe A:7 (Figure 1). A total of 168 pairs of type 2 (heeled shoes) were purchased, with 124 of those shoes being a heel shoe B:1 (Figure 1), and 156 pairs of type 3 (casual shoes) were purchased, with 120 of those being Ugg boots C:6 (Figure 1).

Flat shoes were worn every day as were comfort shoes, and heeled shoes were worn 2–3 times a week. Exploration of the data using Cochran's Q test demonstrated a non-significant association between choice of heeled shoe footwear ($Q = 80.16$; asymptotic significance = 0.000; $p > 0.05$), flat shoe footwear ($Q = 62.43$; asymptotic significance = 0.000; $p > 0.05$) and casual ($Q = 75.90$; asymptotic significance = 0.000; $p > 0.05$). However, further frequency analysis accepted the following footwear choices that heeled shoes were chosen for party and occasion wear, flat shoes were used for school and casual shoes were used for comfort (Table 1).

Choice of purchased footwear

From the completed questionnaires related to the investigation of whether a significant relationship existed between emotional influence and the purchase of the participants chosen shoe, the percentage of participants who chose to discuss group 1 (flat shoes) was 27 per cent, group 2 (heeled shoes) was 33 per cent and group 3 (casual shoes) was 40 per cent. Kruskal–Wallis test revealed that there were statistically significant differences between the groups with group 3 recording higher median score ($Md = 3$) for feeling content and cheerful and group 2 (heeled shoe) for feeling cheerful. How the shoe feels and heel height presented with higher median scores in group 3 (casual

Table 2. Median score of emotions and shoe quality for each shoe category

	Shoe type			Chi-squared	Significance
	1 (flat), *n* = 29	2 (heels), *n* = 29	3 (casual), *n* = 45		
Emotion					
Content	2.00	2.00	3.00	7.180	0.028
Embarrassed	0.00	0.00	0.00	2.116	0.347
Happy	3.00	3.00	3.00	9.343	0.009
Sad	0.00	0.00	0.00	5.310	0.070
Self-conscious	0.00	0.00	0.00	0.789	0.674
Disappointed	0.00	0.00	0.00	1.871	0.392
Proud	2.00	2.00	2.00	2.854	0.240
Cheerful	1.00	3.00	3.00	10.224	0.006
Dejected	0.00	0.00	0.00	4.936	0.085
Shoe quality					
Comfort	4.00	3.00	4.00	19.854	0.000
Fit	4.00	4.00	4.00	1.623	0.444
Value	4.00	4.00	4.00	2.641	0.267
Support	3.00	3.00	4.00	12.473	0.002
Cushion	3.00	2.00	4.00	14.59	0.001
Colour	5.00	4.00	4.00	4.664	0.097
Brand	2.00	2.00	2.00	6.115	0.047
Feel	4.00	3.00	4.00	11.527	0.003
Heel	4.00	4.00	3.00	8.287	0.016
Activity	4.00	3.00	4.00	1.592	0.451
Fashion	4.00	4.00	4.00	0.109	0.947

shoes) for support, cushion, feel of the shoe and activity. Heel height was important in shoe type 2 (heels) with a higher median observed. Principal component analysis (Kaiser–Meyer–Olkin value 0.815 with statistical significance of Bartlett's test of sphericity) highlighted that a two-component solution explained 55.66 per cent of the variance with strong loadings for comfort, support, cushion and feel (Table 2).

To identify further in which group the significance of the choice lay, a Mann–Whitney *U* test highlighted that when comparing group 1 (flat shoes) and group 2, subjects felt that group 2 (heeled shoes) made them happy (U = 241.50; p = 0.004), cheerful (U = 219.000; p = 0.001) and feel good about themselves (U = 258.000; p = 0.009). However, participants felt that the flat shoes were more comfortable (U = 237.000; p = 0.003). When comparing group 1 (flat shoes) and group 3 (casual shoes), it was identified that casual shoes were chosen for cushioning (U = 410.500; p = 0.006), brand (U = 438.500; p = 0.016) and support (U = 430.000; p = 0.011). Yet the heel height of group 1 (flat shoes) was found to be more statistically significant (U = 413.000; p = 0.007) than group 2 (heeled shoes) or group 3 (casual shoes). Group 3 was chosen for comfort (U = 277.500; p = 0.000), support (U = 365.500; p = 0.001), cushioning (U = 346.000; p = 0.001) and the feel of the shoe (U = 372.000; p = 0.001) over group 2 (heeled shoes).

Discussion

Footwear plays an important role in the image of teenage girls. This study has highlighted the presence of some interesting and statistically significant factors associated with fashion and style that influence shoe purchases and the positive effect the chosen shoes have on how participants feel when wearing varying shoe styles.

However, one of the aims of this study was to investigate how foot sizing and shoe fitting correlated as poor fitting footwear is considered a strong factor in the development of foot pathology (Paiva de Castro et al., 2010; Mickle et al., 2011). The results from this study indicated that foot measurements were not seen as an important consideration for footwear purchases. Although many of the participants did indicate a fluctuation in the size of the shoe that they choose to give a better fit and improved comfort, having the foot measured prior to purchasing the shoe was not observed as a common practice in the group studied. This could be attributed to the lack of availability of shoe fitting services within the fashion shoe market. Furthermore, satisfaction rates were high regarding fit and therefore self-selection of footwear size is an accepted method of shoe fitting.

Fitting has been identified as region-dependent and segments of the shoe that alter in sizing can alter perceived comfort (Au and Goonetilleke, 2007); therefore, a change in dimension in the arch or toe box may make the same size shoe feel comfortable or not. This observed alteration in shoe sizing could also be correlated with the changes in style and design of the shoe choice made. There is no standard shoe sizing system used in the manufacture of shoes worldwide and last development has been slow to evolve to current populations; therefore, the shoe sizing can vary from brand and manufacturer. It has been shown that toe box shape and dimension can influence fit (Paiva de Castro et al., 2010), and ill-fitting shoes are correlated with foot pain and deformity (Mickle et al., 2011). The styles adopted by designers have varied over time regarding toe box shape. Acute-shaped toe box points were popular as ‘winkle pickers’ in the 1960s and have been correlated to the belief that the pointed shoe can cause joint deformity (Marfat, 2007). Although this study did not investigate the choice of footwear shape, which has been associated with perceived comfort (Witana et al., 2009), at the toe box, the current trend on the UK high street is for a rounded toe box, and this type of shoe style would not cause such pressure on toes, and therefore, a reduction in toe deformities may be seen later in life if the habitual wear of round-toed shoes continues (Al-Abdulwahab et al., 2000).

Foot sizing has already been recognised in the literature as being related to image in different cultures, small feet were considered more desirable in the Chinese population where binding the foot to prevent growth has been current practice for centuries. Elbrey (1999) has reported that there is a theoretical relationship between elegance and virtue associated with a smaller foot, with a larger foot deemed as clumsy and alien like. This study showed no evidence that footwear sizing influenced image in such a way. However, on analysing foot sizing as a predictor of shoe size, there was statistically significant evidence that left foot length was a strong predictor of shoe size. This highlights that the shoe outlets that do not provide a fitting service for customers could assist in better fitting of footwear by displaying the shoes for the left foot, which will enable purchasers a more realistic assessment of comfort and fit.

The participants’ choices of activity for which that the chosen shoes were selected were reflected in the frequency with which each shoe type was worn. Flat shoes were generally chosen for school wear to be used every day and this style of shoe was seen as comfortable and well fitting. Using a shoe as part of a uniform can detract from the positive feelings associated with image; this was seen in the emotion analysis where the casual shoe group did not have any significant emotions associated with its use. Stipulation of school rules may influence the choices that the participants can make regarding uniform and fashion. If the school uniform rules do not have any flexibility to allow for an expression of self-image, then there may be a negative emotion attached to wearing that item. The negative emotions did not score high for this shoe type although there is not a strong trend to rebel against using this style of shoe for school, and the participants have found an acceptable style to wear for school. Style A:7 ballerina pump was the most frequent flat shoe chosen and this style has minimal volume upper, no fastening and limited support for all the factors that have been associated with foot pain and weakness (Menz and Morris, 2005; Mickle et al., 2011; Paiva de Castro et al., 2010). By not supporting the foot, even when flat, with a shoe fastening the foot changes shape to keep the shoe on to the foot. Modifications in shoe volume and style can be seen in slip on shoes to help the wearer keep the shoe on the foot, this style of shoe has already been identified as being directly correlated to pain in the older adult (Dufour et al., 2009), which may be due to a prolonged habitual change in foot function over a life time.

The data from the high-heeled shoe group, however, showed a statistically significant relationship between shoe choice for a specific activity (in this instance, parties and social occasions) and the height of the shoe heel. Heel height has previously been found to be associated with feelings of heightened sexuality, sophistication and power of the wearer (Yorkston, 2010). It is thought that the high-heeled shoe extends the length of the leg and alters the pelvic position to enhance female body shape. As well as increasing the height of a smaller individual, these changes in body position, could it might be argued, empower the individual creating a difference in image and self-esteem. Analyses of the results indicated that the choices the participants made for wearing high heels in this study would suggest that this population of interest use the heeled shoe to enhance sexuality and self-image while engaging in social activities.

This shoe has been strongly related to musculoskeletal pathology and postural complaints (Lee et al., 2001; Linder and Saltzman, 1998; Mandato and Nester, 1999). Frequent and use early in the life cycle of an adult may have negative implications into the long-term development of joint and muscle complaints. The long-term effects of wearing high heels have been shown to change calf muscle length and can be related to long-term stiffness in the Achilles tendon (Csapo et al., 2010). The participants in this study, although choosing the heeled shoe for parties and occasions, indicated that this style of shoe could be worn 3–4 times a week. Searches of the literature have failed, however, to provide any data to indicate how frequently or for how long a heeled shoe needs to be worn for pathological changes to occur. Muscular and skeletal changes that can occur as a result of wearing high heels would not necessarily be important to younger wearers.

Casual shoes were primarily worn over the weekend for a more informal appearance with the Ugg boot being most frequently chosen. Influential popular celebrities as well as commercial marketing and branding can all have a significant impact on purchases made by the teenage population (Yoh, 2005). Although the Ugg boot is not supported heavily by a strong marketing campaign, the popularity of this boot has been a global phenomenon. Comfort was significantly important as a factor when choosing this shoe. Material choice that enhances comfort would help to play a strong role when purchasing this style of boots. Further research into the suggested lack of support this boot style gives the wearer is required to substantiate claims that the long-term use of this boot may be detrimental.

Research limitations

Conducting this research solely via a questionnaire limited the scope of data collected. Interviews and focus groups might have provided more depth of information as to the influential factors and body image considerations when purchasing shoes. The current format, however, did provide an informative base to proceed with future studies on the role footwear plays in the image and identity.

Conclusions

Footwear choices in teenage girls are predominantly activity based and are strongly associated with comfort, feel and cushioning. Results indicated that such shoes were more likely to make teenage girls feel happy and cheerful and have a positive impact on self-esteem. From the shoes studied, the results show that the significant majority of teenage girls like to wear flat ballet style pumps for school, high-heeled shoes for parties and occasions and wool boots for weekend casual wear. Further work is recommended to investigate in greater depth the impact of wearing differing shoe styles has on body image and pathology.

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Appendix 8

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JOURNAL OF FOOT AND ANKLE RESEARCH

RESEARCH **Open Access**

The effect of three different toe props on plantar pressure and patient comfort

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Abstract

Background: Arthritic toe pathologies frequently lead to the development of painful apical pressure skin lesions that can compromise gait and affect quality of life. Historically conservative treatments involve the use of a toe prop with the intended aim of reducing plantar pressure from the apex of the digit. However, the effect of toe prop treatment on plantar digital pressure has not been investigated.

Method: Twenty two subjects were recruited with lesser digital deformities and associated apical skin lesions. Individual pressure sensors were placed on the apices of the lesser toes and pressure was recorded under three toe prop conditions (leather, gel and silicone mould). A modified comfort index was utilised to assess the comfort of each condition.

Results: Significant difference ($p < 0.05$) in mean peak pressure was observed at the apex of the 2nd toe when using the gel ($p < 0.001$) and silicone ($p < 0.001$) toe prop compared to no toe prop. There was also a significant difference in the mean pressure time integral at the apex of the 2nd toe when using gel ($p < 0.001$) and silicone ($p < 0.004$) toe props. There was no significant correlation between comfort and the recorded peak pressures. However, there was an indication that the silicone toe prop was more comfortable.

Conclusion: As compared to the leather and silicone mould toe props, gel toe props were found to be the most effective for reducing peak pressure and pressure time integral on the apex of the second digit in patients with claw or hammer toe deformity.

Keywords: Apical peak pressure, Digital deformities, Toe prop therapy, Comfort

Background

Toes play an important role in dynamic foot function by increasing the weight bearing area of the forefoot. This increased area allows for sufficient plantar pressure to be exerted over a fixed point from which the body can then be propelled forward [1,2]. The digits stability and plantar flexion movements in a healthy foot that give this propulsion are controlled by the foot flexor muscles and plantar fascia arrangement [2-4].

The development of painful arthritic toe pathologies occurs over a long period of time, where alterations in propulsion can change joint positions. This can lead to pressure related skin lesions that compromise gait and can affect quality of life [5]. Digital deformities in the sagittal plane include claw, hammer, retracted and mallet toes. These digital deformities are diagnosed depending on which digital joint is maintained in a flexed or extended position. A claw toe is a flexus digitus deformity involving hyperextension of the metatarso-phalangeal joint (MTP) combined with flexion of the distal and proximal interphalangeal joints (IP) [6]. A hammered toe involves hyperextension of the MTP Joint and a flexion deformity of the proximal IP Joint, however there is no flexion deformity at the distal IP joint [6-8].

Clawed and hammered digits are more frequently associated with apical lesions particularly in the second digit which can bear 25% of digital peak plantar pressure and can be a main source of discomfort in the forefoot [1,9-11]. In these digital deformities the apex of the toe comes into contact with the ground first rather than the plantar fat pad that protects the distal phalanx. This increases the apical plantar pressure by reducing the contact area of the digit [8]. Retracted and mallet digital

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deformities do not present with such increased plantar pressure and apical lesions are therefore less common in these two type of deformities.

Skin lesions forming on the apex of the digit are a result of hyperkeratosis (locally increased rate of proliferation of keratinocytes), a normal physiologic response of the skin to chronic excessive pressure [12]. If pressure and tissue stress continue over time without symptom relief then the tissue can ulcerate and in some cases this can lead to toe amputation [13,14]. Off-loading pressure from the apex of the digit provides an indispensable precondition both for encouraging the tissue-repair mechanism, where active lesions are present, and also for stopping the potential progression of pre-ulcerative conditions toward lesions [12].

Toe props have been used to treat painful apical skin lesions for over 80 years and are placed under the claw or hammer digit with an aim to decrease plantar digital pressure [15-18]. Different types of toe props used for the treatment of apical lesions vary extensively. In clinical practice the size of the toe prop fitted depends on the length of digit, severity of the clawing and the comfort of the prop. A toe prop which is too large or ill fitting may well reduce apical pressure, as the toe apex will not touch the ground, but increased bulk can restrict function of the digits, create dorsal lesions and be uncomfortable to wear. A correctly fitted toe prop (shape and size) is still likely to reduce apical pressure and coincide with a better functioning toe increasing the comfort of the prop.

To date there has been minimal research into the actual effect of the toe prop on apical pressure and the practice of apical lesion management with a toe prop is mainly based on tradition. A further understanding of pressure reduction, comfort and effect of different toe props will enhance clinical practice in the management of digital foot pain. The aim of this study is to investigate the effect of 3 toe props regularly used in clinical practice for the treatment of callus related to apical pressures in subjects who have been diagnosed with either claw or hammer digital deformities. Additionally, the comfort of the props used will also be assessed as the reduction in pressure with a toe prop is known clinically for not always being tolerated by the patient.

Methods

Prior to commencing this study ethical approval was sought and granted by Staffordshire University Research Ethics Committee, Stoke-on-Trent, UK. All subjects recruited provided written informed consent prior to the participation in this study.

A repeated measures design was employed to allow comparisons between the three toe prop conditions. Twenty two subjects (18 female: 4 male. Age 68 SD +/− 10years. Weight 73.21 kg SD +/− 10.5 kg. Height 168.4 cm SD+/− 8.82cm.) were recruited from a clinical population. All subjects presented with clawing/hammer of all lesser digits (second third fourth and fifth). The frequency of prominent digital deformities over the other digits included; second $n = 9$, third $n = 2$, fourth $n = 2$ and fifth $n = 3$. Hyperkeratotic lesions were present in frequency on the apex of the second $n = 12$, third $n = 11$, fourth $n = 1$ and fifth $n = 0$. Subjects were excluded if they had no apical lesion, complex ulcerations, foot surgical intervention, inappropriate footwear and an inability to walk unaided.

Subject preparation

One week prior to data collection all recruited subjects received debridement of the apical lesion. This allowed for all subjects to be relieved from any direct pain related to the apical lesion. There have been mixed results regarding callus removal with reports supporting and negating the benefit of callus removal on pressure [13,19]. To gain a comparable comfort score removal of callus was deemed appropriate. Digital deformity was recorded as either flexible or rigid at each of the proximal and distal interphalangeal joints. Footwear was not standardised to portray an appropriate everyday lifestyle condition. Subjects own footwear used in the study was assessed for depth, width and length. Subjects were excluded if the footwear was tight and influenced toe spacing and depth.

All recruited subjects were fitted with three types of toe props to be researched (Figures 1, 2 and 3). Leather and gel toe props are preformed devices that are fitted based on foot and digit size. Silicone mould toe props are bespoke and individually molded to the digit. To keep within repeated measure design the prefabricated measured toe props (leather and gel) were assessed for fit by evaluating the position in relation to the plantigrade

Figure 1 Leather toe prop. Leather toe props were fitted to digit size and were plantigrade with 3rd metatarsal head.

Figure 2 Gel toe prop. Gel toe props were similarly fitted to digit size and plantigrade with 3rd metatarsal.

surface of the foot. A flush prop with the plantar third metatarsal head was classified as suitable, anything protruding or regressing from the plantar surface was refitted. Silicone moulds were manufactured for 2, 3, and 4 digits with the silicone spread evenly on to the apices of the distal phalanges with no added bulk under the proximal phalanges. The size, shape and form can vary with each patient depending on the participants toe structure therefore to minimize variance all toe props were dispensed by the same researcher.

Data collection

A week after preparation, data were collected for each subject for each toe prop condition and a no toe prop condition (as control). Prior to testing all subjects were asked to complete a visual analogue scale, modified comfort index [20]. The scale evaluated the comfort of 10 parameters associated with the toe prop fit, size and feel and is based on a visual analogue scale of 10 cm. The line is a representation of how comfortable the toe prop is from 0 cm being very uncomfortable to 10 cm being very comfortable. A cumulative score from each parameter is generated and is an indication of overall comfort. A maximum score of 100 indicates extreme comfort.

Figure 3 Silicone toe prop. Silicone toe props were individually molded to the contours of the digits.

Toe prop conditions were randomly allocated by the subject picking a card blinded to the researcher identifying the trial condition. Cards were continued to be picked until a full order of testing conditions was obtained. After each toe prop condition was applied to the digits the subjects were asked to walk around for 2 minutes and evaluate each condition for comfort. This was again collected using the comfort index.

On completion of recording the comfort score, plantar pressure data were collected using Walkinsense (Tomorrow Options Microelectronics, S.A. Sheffield, UK). The sensors are individual piezoresistive force 100Hz sensors that were attached to the apices of each lesser toe 1–4 (Figure 4). The sensors are comparable to other plantar pressure systems but caution should be taken for a direct comparison of results between software [21]. The foot was cleaned and adhesive spray was applied to improve adhesion of the sensors. These sensors were connected to a wireless blue tooth device on the ankle, which is held in place by a Velcro strapping [21]. Proprietary software supplied by the manufacturers was set to receive data corresponding to the foot tested. Pressure data were collected whilst the subject walked at a self selected speed along a 10 meter walkway. From this data eight foot falls were recorded.

Data analysis

Statistical analysis was conducted using SPSS (IBM v 19) software. Tests for normality to ensure the assumptions

Figure 4 Sensor placement: 1 = Apex of second digit, 2 = Apex of third digit, 3 = Apex of fourth digit and 4 = Apex of fifth digit.

of parametric testing were met included the Kolmogorov-Smirnov statistic (>0.5 indicating normality). For data that met the assumptions parametric testing was implemented, for all data that did not meet the assumptions for normality non parametric equivalents were applied.

For each toe prop variable the comfort results were analysed using a non parametric Friedman test, alpha set at 0.05.

After removing the first and last steps, three foot falls with comparable pressure data were extracted, analysed and averaged [22]. The mean peak pressure and pressure time integral were calculated for each sensor in each of the four conditions. This data was statistically analysed using a one way repeated measure analysis (ANOVA) with alpha set at 0.05.

Results

Mean plantar digital peak pressure

The mean plantar digital peak pressure for each sensor is reported in Figure 5. For all sensors the leather toe prop reduced peak pressure from the no toe prop condition. The gel toe prop also reduced mean peak plantar digital pressure for all sensors accept sensor 4. The silicone toe prop reduced mean peak plantar digital pressure compared to no toe prop condition for sensor 1 only, sensor 2,3 and 4 recorded higher mean peak plantar digital pressure. Significant difference in mean peak apical pressure at the apex of the 2nd toe (sensor 1) (Wilks' Lambda = .27, F (3,19) = 16.38, $p < 0.001$, multivariate partial eta squared = .72) was observed. Significance was seen when introducing the gel and silicone toe prop conditions. There was no statistical significant difference between toe prop conditions for mean peak apical pressure at the apex of the third fourth and fifth (sensor 2,3 and 4).

Mean plantar digital pressure time integral

The mean pressure time integral followed a similar trend to peak pressure with leather and gel toe props reducing the pressure time integral when compared to the control and silicone only achieving a reduction at apex of second digit (sensor 1) Figure 6. The results for apex 5th digit (sensor 4) however, indicate an increase in the pressure time integral for the gel and silicone toe props. A significant difference was also observed in the mean pressure time integral at the apex of the 2nd toe (sensor 1) (Wilks' Lambda = .32, F (3,19) = 13.48, $p < 0.001$, multivariate partial eta squared = .68). The significance differences were seen whilst introducing the gel and silicone toe props. Again, there was no significant difference between conditions for mean pressure time integral at the apex of the third fourth and fifth (sensor 2,3 and 4).

Comfort index

The scatter graph Figure 7 highlights the lack of relationship for the comfort of each condition. Each subject indicated different comfort scores for each of the toe props tested. There was little or no trend to be observed between conditions. It was found that 32% (n = 7) of subjects using a toe prop were more comfortable when compared to the control condition, with no specific trend between which toe prop was most comfortable. Similarly, 18% (n = 4) found the control condition more comfortable than any of the toe prop conditions. The statistical analysis using the Friedman test indicated there was no significant difference in the comfort scores across the four variables measured ($p > 0.536$. χ^2 (3,n = 22) = 2.18, $p < .0.005$). Median values between control ($Md = 36.5$) and gel ($Md = 29.8$) leather ($Md = 28.1$) decreased. There was an increase in values for silicone ($Md = 37.6$) suggesting there may be a relationship in comfort for silicone toe props.

Correlation between comfort and peak pressure

When comparing the recorded mean peak plantar digital pressure for the apex of the second digit (sensor 1) with the reported comfort scores for each variable there was no relationship observed. A Spearman rho correlation

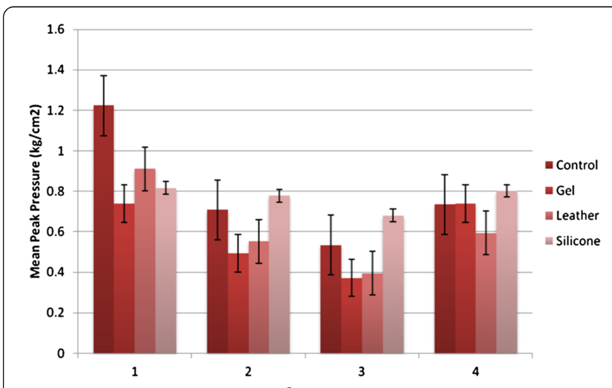

Figure 5 Mean Peak pressure results. Mean Peak Pressure for each sensor for each condition with error bars.

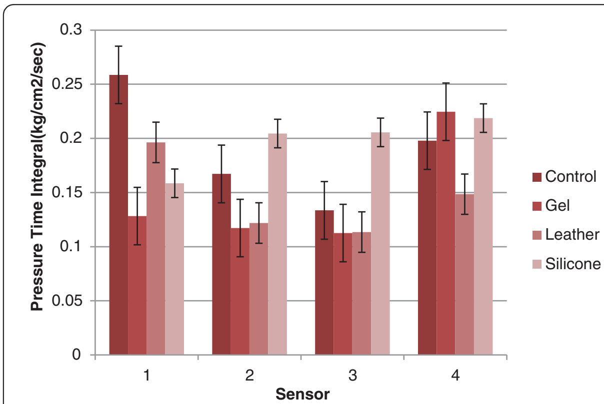

Figure 6 Pressure time integral results. Pressure Time Integral for each sensor for each condition with error bars.

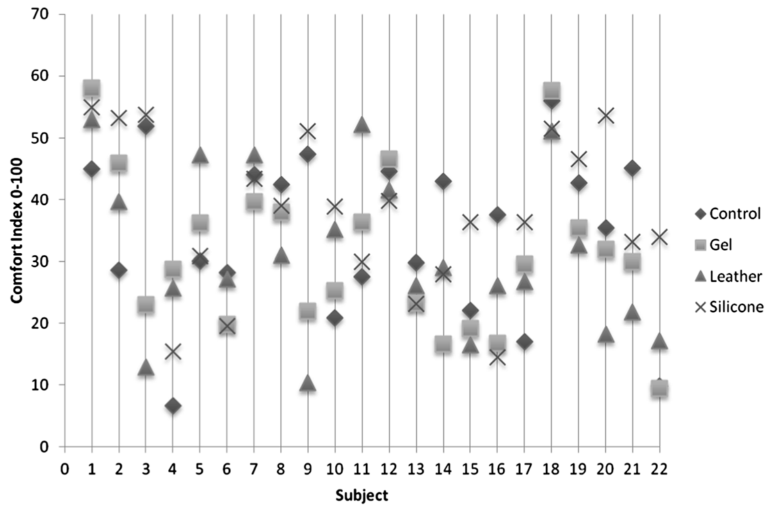

Figure 7 Comfort Scores. Comfort scores for each subject for each condition. The smaller the score the less comfortable the prop the higher score favours more comfort.

coefficient between mean peak plantar digital pressure and comfort for no toe prop $r = 0.131$, gel $r = 0.74$, leather $r = 0.158$ and silicone $r = 0.15$ showing no correlation between mean peak plantar digital pressure and comfort.

Discussion

The results from this study highlight a significant reduction in peak plantar digital pressure and plantar digital pressure time integral on the apex of the second digit for the gel and silicone toe prop conditions. This demonstrates that the use of silicone and gel toe props are the most suitable current treatments when the desired objective is to reduce peak plantar digital pressure as well as pressure time integral for lesions on the apex on the second digit.

Lesion formation on the apex of digits has been associated to the amount of time pressure is raised in an area rather than the quantity of pressure [17,23]. A prolonged period of time under pressure deforms skin cells and instigates a hyperkeratotic response leading to the formation of callus and corns. If the lesion is not removed and the pressure continues the cells deform further breaking the epidermis and ulcerating the skin [12,13]. By reducing the peak pressure and pressure time integral this mechanism can be resolved and the patient's symptoms are relieved. The three toe props investigated in this study are regularly used in clinical practice with understanding based on traditional concepts rather than research. Often toe props are dispensed on patient preference and past experience rather than clinical measures of reduced plantar digital pressure. This study has provided additional knowledge as to the effectiveness of toe props utilised in practice.

Although plantar digital pressure was reduced with silicone and gel toe props, patient compliance and comfort are often more important to the success of the treatment. Poor compliance often leads to the perception of the treatment being ineffective. Foot orthoses have been shown to be worn more when they are perceived as comfortable, delivering positive outcome measures to the success of the treatment [24]. Therefore making an effective treatment comfortable will enhance patient compliance and the outcomes achieved. This study highlighted no significant correlation between perceived comfort and reduction in pressure therefore it is not advisable to evaluate the impact of pressure reduction by the reported comfort level of the device. However it can be accepted that patients will not tolerate a toe prop device that is very effective in reducing pressure if it is not comfortable.

Furthermore, comfort analysis indicated that subjects found the silicone devices to be marginally more comfortable than the gel and leather toe props. With the knowledge that there was no significant change in peak pressure or pressure time integral when using a leather toe prop it could be further concluded that this prop has no clinical use for lesions on the 2nd apex and should be replaced with a gel or silicone device that has been shown to reduce plantar digital pressure when treating apical lesions on the second digit.

The higher comfort index associated with silicone prop may also be in part due to the results of a higher contact surface area between the digits and the moulded silicone prop. The silicone prop covers the whole plantar surface of digits, whereas the gel and leather do not. The moulding technique, through which this kind of prop is manufactured, provides a bespoke contact surface area with the digits while complying with the shape of the lesser toes. This may increase the comfort associated with distributing the ground reaction force over a larger plantar surface and providing support in between the digits. Further studies are warranted to assess the effect of toe props on the plantar and digital pressure as well as interdigital. In such studies visco-elastic properties of the material which the prop is made off as well as the application technique that determined the geometry and contact area needs to be considered and scrutinised.

The population sampled in this study presented with a variety of toe deformities, all subjects had claw/hammer lesser toes with a prevalence of second toe deformities. Apical lesions were seen most frequently on the apex of the second digit which can bear 25% of digital peak plantar pressure and can be a main source of discomfort in the forefoot [1,9-11]. The success of the toe props in significantly reducing pressure in this area could be related to the type and frequency of this deformity within the population sampled. Although there were apical lesions present on the third digit also, this was not seen as a predominately deformed toe and could be associated with abnormal pressure at the second digit. Therefore, the distribution of second digital apex lesions within the sampled population may have promoted the significance of the results and further studies focusing on high frequency lesions on the third fourth and fifth apex are recommended.

Conclusions

It can be concluded that the results of this study have demonstrated that there is a significant reduction in mean peak plantar digital pressure and pressure time integral on the apex of the second digit when using a gel and silicone toe prop. Furthermore from the sample studied the silicone toe prop was identified as more comfortable than the gel and leather toe props. It can therefore be recommended that the silicone toe prop is used as a primary treatment for second toe apical lesions associated with elevated peak plantar digital pressure and pressure time integrals.

Competing interests

All authors involved in this manuscript can declare that they had no competing interests.

Authors' contributions

SJ and HB designed and conducted the study. SJ, HB and RN processed and analysed the data including statistical analysis. SJ, HB, NC produced and revised the manuscript. All authors reviewed the final manuscript before submission.

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Appendix 9

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Evaluation of lower limb electromyographic activity when using unstable shoes for the first time: A pilot quasi control trial

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Abstract

Background: Unstable shoes, which have recently become popular, claim to provide additional physiological and biomechanical advantages to people who wear them. Alterations in postural stability have been shown when using the shoe after training. However, the immediate effect on muscle activity when walking in unstable shoes for the first time has not been investigated.

Objective: To evaluate muscle activity and temporal parameters of gait when wearing Masai Barefoot Technology shoes® for the first time compared to the subject's own regular trainer shoes.

Study Design: A pilot repeated-measures quasi control trial.

Method: Electromyographic measurements of lower leg muscles (soleus, medial gastrocnemius, lateral gastrocnemius, tibialis anterior, peroneus longus, rectus femoris, biceps femoris and gluteus medius) were measured in 15 healthy participants using Masai Barefoot Technology shoes and trainer shoes over a 10-m walkway. Muscle activity of the third and sixth steps was used to study the difference in behaviour of the muscles under the two shoe conditions. Temporal parameters were captured with footswitches to highlight heel strike, heel lift and toe off. Paired samples *t*-test was completed to compare mean muscle activity for Masai Barefoot Technology and trainer shoes.

Results: Indicated that the use of Masai Barefoot Technology shoes increased the intensity of the magnitude of muscle activity. While this increase in the activity was not significant across the subjects, there were inter-individual differences in muscle activity. This variance between the participants demonstrates that some subjects do alter muscle behaviour while wearing such shoes.

Conclusion: A more rigorous and specific assessment is required when advising patients to purchase the Masai Barefoot Technology shoe. Not all subjects respond positively to using unstable shoes, and the point in time when muscle behaviour can change is variable.

Clinical relevance

Use of Masai Barefoot Technology shoe in patient management should be monitored closely as the individual muscle changes and the point in time when changes occur vary between subjects, and evaluation of how a subject responds is not yet clear.

Keywords

Masai Barefoot Technology shoes, electromyography, muscle activity

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Introduction

Over the past decade, a new market has opened into developing footwear that claims to provide the user with a body workout while walking in specifically designed shoe. An irregular and unstable sole is thought to change the interaction between the foot and the ground. On wearing such shoes, these changes have been hypothesised to alter muscle

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function and contraction, making the lower limb muscles work harder. However, it is not clear from the research carried out so far what the specific effects of wearing unstable shoes have on lower limb muscle activity and contraction timing while walking.

The unstable shoe concept was originally launched with the Masai Barefoot Technology (MBT) shoe® that has a curved outer sole in the anterior–posterior direction and a dual-density heel profile. Research, to date, has primarily focused on the trained effects of the MBT shoe over a period of time on posture and muscle activity in stance.[1–4] After a trained period of using the MBT shoe, there have been observed alterations in standing with anterior and posterior sway increasing suggesting that the shoe has an impact on stability and balance.[1,5]

The effect of the MBT shoe while standing on external foot muscles was investigated after a 6-week adaptation period, using an electromyographic (EMG) circumferential linear array with magnetic resonance imaging (MRI) scanning. The activity of the soleus (SOL) muscle remained unchanged when wearing the shoe, yet there was increased activity in the anterior leg compartment and peroneal muscle group, suggesting that these muscles are recruited as a method to improve stability.[6] Although this increase in muscle activity when standing in unstable shoes may be beneficial to some users, the full impact of wearing the MBT shoe while walking still remains unclear.

Improved postural stability, while walking, has been indicated in other unstable shoes such as the Reflex Control shoe.[4] This shoe was used over a 6-week intervention programme and was found to improve posture and balance when compared to the MBT shoe. Furthermore, the instability of this shoe differs to that of the MBT shoe with the mode of instability being along the longitudinal axis of the foot. Although this study introduced a dynamic component to postural stability with a moveable plate, the testing did not include gait trials, and therefore, the results should be used with caution when discussing the effects of unstable shoes on gait.

Analysis of gait in subjects who had been trained for walking in MBT shoes for a 4-week period were found to have a smaller step length and altered ankle range of motion with increased amount of dorsiflexion.[2] This altered range of motion has also been highlighted when testing MBT sandals. Subtalar and ankle sagittal plane motions increased when wearing the sandal compared to barefoot trials.[7]

More recently, it has been suggested that there is a great variability between subjects when studying the effects of walking in MBT shoes with outcomes being subject dependent.[3] Again, subjects were given a period of time to become accustomed to using the shoe, and testing occurred after a training period. The changes that were observed between subjects have been linked to different strategies of compensation being employed by the individuals wearing the shoe.[1,8] Different strategies have also been adopted between various subject groups. When studying the changes between female and male subjects who were trained in using the MBT shoe, it was found that female users had greater anterior–posterior excursion of centre of pressure than males and altered control around the ankle joint.[5] However, the effects while walking after a period of training in the shoe appear to be varied and subject dependent. There is limited research to indicate exactly when habituation occurs and whether those subjects who have increased muscle activity adapted immediately or over a period of time.

Previous studies have focused on the effects of the shoes after a period of training or adaptation and are unable to make specific recommendation with respect to the usefulness of the MBT shoe while walking. The immediate effect of wearing the MBT shoe has recently been investigated, yet the subjects were allowed to become habituated prior to data collection.[9] If the MBT shoe is to be considered as a rehabilitation or training device, it is not clear from previous work as to how quickly muscle habituation occurs. This is important to distinguish how to use the MBT shoe in a clinical situation as a treatment modality as impact on patient rehabilitation needs to be considered.

The aim of this study, therefore, is to identify whether the activity of eight lower limb muscles alter while walking in the MBT shoe for the first time without any habituation period. This will test the hypothesis that a change in muscle activity while wearing the MBT shoes will occur immediately. The secondary objective of this study is to evaluate temporal parameters of gait between a regular trainer shoe and an MBT shoe during walking.

Method

Design

A quasi-experimental study with two repeated measures, where each subject acted as their own control. Ethical approval was sought and given by the University Ethics Committee, and all subjects provided a written informed consent.

Inclusion criteria

Subjects were recruited from a convenience sample of healthy student population who were able to stand on one leg and rise on to the toes without falling and have no musculoskeletal injury or pathology. All subjects had not worn the MBT shoe prior to testing.

Exclusion criteria

Subjects were excluded if they were unable to stand on one leg, had used the MBT shoe previously and were currently injured or had an injury within the last 6 months.

Outcome measures

The following outcome measures were reordered: number of steps taken in each shoe condition, mean EMG activity for each muscle, percentage change in muscle activity and time at which heel strike, heel lift and toe off occurred between the control and MBT shoes.

Study protocol

In total, 20 volunteers (male, n = 12; female, n = 8) with a mean age of 26 years (standard deviation (SD) = ±5.62 years), mean height of 170 cm (SD = ±7.11 cm), mean weight of 69.8 kg (SD = ±10.5 kg) and a Foot Posture Index (version 6) range between +2 and +12 consented to partake in the project.

Subjects' own training shoe was used as a control measure, which was weighed; the MBT shoes used in this study weighed 1.3 kg. Test leg allocation was randomly assigned with the subject choosing an envelope stating which leg was to be tested. EMG electrode placement was defined using the surface EMG for non-invasive assessment of muscles (SENIAM) guidelines.[10] Accurate placement was made with musculoskeletal ultrasound (MyLab; Esaote, Genoa, Italy) and functional muscle testing,[11] which allowed reporting of reliable and valid data. Bipolar electrodes were placed directly on to the skin that had been prepared with an alcohol wipe. The following muscles were selected for investigation based on previous studies that had investigated EMG muscle activity, and additional muscles were included, which are known to be involved in key stages of gait that had not been previously studied.

- SOL
- Medial gastrocnemius (MG)
- Lateral gastrocnemius (LG)
- Tibialis anterior (TA)
- Peroneus longus (PL)
- Rectus femoris (RF)
- Biceps femoris (BF)
- Gluteus medius (GMed)

A footswitch was used to identify heel strike, heel lift and toe off, sensors were placed on the plantar posterior aspect of the calcaneus (sensor 1), the plantar aspect of the first met head (sensor 2) and also the plantar aspect of the apex of the first digit (sensor 3). The subject then replaced the sock over the sensors. Testing commenced with the subject walking in the trainer shoes along a 10-m walkway at a self-selected pace. The subject then placed the MBT shoes on and immediately walked again along the 10-m walkway.

Data processing and analysis

The number of steps taken over the 10-m walkway was identified from the EMG data. For data analysis, two steps were analysed as a representation of activity (the third and the sixth step) for each condition. These middle steps were selected to remove the acceleration and deceleration seen at the beginning and end of the walkway. Data collected from the EMG, sampled at 2048 Hz, of the eight muscles were notch filtered and rectified prior to passing through a 10-Hz eighth-order Butterworth filter. These data along with footswitch data were processed offline in a custom-developed program in MathCAD (Version 15; PTC, Needham, MA, USA). The footswitch data were used to identify key phases of the gait cycle, heel strike, heel off and toe off. The mean and maximum values were obtained for each muscle during a full gait cycle (defined as heel strike to heel strike). The mean EMG value was then calculated as a percentage value of the maximum EMG value recorded in the analysed trials.

As data met parametric assumptions, a paired samples t-test for mean EMG activity was used to identify differences between the control shoe and the unstable MBT shoe for each muscle (significant at $p > 0.05$). Additionally, differences between time at which heel strike, heel off and toe off occurred were also compared using a paired samples t-test.

Results

From the 20 subjects recruited, 5 were excluded due to inconsistencies with EMG data collection and outliers, therefore n = 15 (age = 25.2 years, SD = ±5.2 years; height = 168.36 cm, SD = ±6.7 cm; weight = 66 kg, SD = ±10.6 kg; control shoe weight range between 0.3 and 0.8 kg; right: left leg measured = 10 : 5).

Steps taken

The average number of steps taken in the control shoe is 9 (SD = 0.89), and in the MBT shoe, it is 8.69 (SD = 0.87). The distribution of this change included four subjects taking more steps while wearing the MBT shoe, eight subjects taking less steps and four subjects not altering the steps taken.

Mean EMG

Mean activity between the trainer shoe and MBT shoe increased in SOL, MG, PL, RF and GMed. Activity in LG stayed the same, and overall activities of TA and BF decreased. Paired t-test, however, showed no significant differences for these recorded values ($p > 0.05$) (Table 1).

Across all the muscles tested, there were an observed group of subjects that had no alteration in the EMG activity between the control shoe and the MBT shoe. Similarly, there was also a group of subjects that had more EMG activity while wearing the trainer shoes. Figure 1(a) to (h) shows scatter plots for the mean activity of each muscle tested for

Table 1. Mean, maximum EMG (mV) and percentage values for each muscle for each condition. Paired *t*-test shows significance at *p* value.

Muscle	Control shoe			MBT shoe			Significance (p > 0.05)
	Mean value	Maximum value	% value	Mean value	Maximum value	% value	
SOL	68.908	245.446	32.018	91.259	250.566	39.934	0.168
MG	68.598	250.741	32.399	79.468	327.407	28.772	0.25
LG	132.624	626.55	25.39	134.541	619.734	28.321	0.942
TA	89.081	279.386	31.956	66.363	214.375	34.465	0.299
PL	67.915	254.676	30.495	79.371	285.332	30.129	0.225
RF	515.012	1648.816	32.197	705.203	2256.528	29.234	0.149
BF	287.006	957.947	28.774	190.186	581.783	30.231	0.149
GMed	94.053	307.764	30.431	195.034	627.294	30.621	0.101

TA: tibialis anterior; PL: peroneus longus; MG: medial gastrocnemius; LG: lateral gastrocnemius; SOL: soleus; RF: rectus femoris; BF: biceps femoris; GMed: gluteus medius; EMG: electromyography; MBT: Masai Barefoot Technology.

each subject ($n = 15$). Demonstrating an inconstant variability in responses between the trainer shoe and MBT shoe conditions. It can be seen from these graphs that some subjects had increased activity while walking in the MBT shoe and others had no change or reduced activity.

Percentage change

As a representation of the work done by each individual muscle, the mean muscle EMG data were calculated as a percentage of the recorded maximum value for that muscle in each shoe condition. This was compared to the mean maximum recorded for the tip toe exercise. Increase in the muscle activity when wearing MBT shoes were seen in SOL, LG, TA and BF. There was no difference in percentage change for PL and GMed and there was a decrease when wearing MBT shoe in MG and RF (Table 1).

Gait timing

Footswitch data showed no significant difference between the timing of heel strike, heel off and toe off between shoe conditions (Table 2). Again, individual patterns of footswitch data showed that 56% of subjects had the same contact time when wearing trainer and MBT shoes, 25% had lower contact in MBT shoe and 19% had higher contact time in MBT shoe. Paired *t*-test showed no significant difference for any of the gait timing events between the trainer and MBT shoes.

Discussion

The hypothesis tested was to identify the immediate reaction of the lower limb muscles when the subject wore the MBT shoe for the first time. Although this hypothesis was statistically not supported from the results, mean muscle activity while wearing MBT shoes showed an increase in activity, in five of the eight muscles studied (SOL, MG, PL, RF and GMed). This increased change agrees with previous work that looked at EMG data while wearing MBT shoes after a 4-week adaptation period, with observed increases in muscle activities in TA and gastrocnemius[2] and GMed,[1] suggesting that the observed changes reported after 4 weeks of training can occur immediately in some subjects.

However, it should be noted that in this study, there was a high level of variability between subjects, and there was no systematic response in EMG activity between conditions. Any changes observed were not consistent throughout the group as previously suggested.[2] Furthermore, it is not clear from the current results which factors determine whether the response from wearing the MBT shoe for the first time will increase, decrease or have no effect on muscle activity and at what point adaptation occurs when wearing the shoe. The variability in muscle EMG seems to be unpredictable as to what effect wearing the MBT shoe will have. This makes assessment of the benefit from wearing such a shoe difficult. Therefore, caution should be taken on suggesting an unstable shoe as a treatment modality, and tight monitoring of patients who use these shoes is recommended.

Subtle differences were seen within this study that may provide some suggestions for the variability seen in EMG activity. The weight of the MBT shoe was in some cases 1 kg heavier than the control trainer shoe used. The four subjects who wore the lightest control shoe did have increased EMG while wearing the MBT shoe but the pattern between these groups of subjects was not consistent to substantiate a claim that the effect of the MBT shoe is due to altered weight. Footwear changes have been noted in previous investigations as a reason for altered muscle activity.[12] Instant changes from a lightweight shoe, which the wearer has adapted to using, to a heavy shoe could induce immediate alteration in muscular activity as a response to the

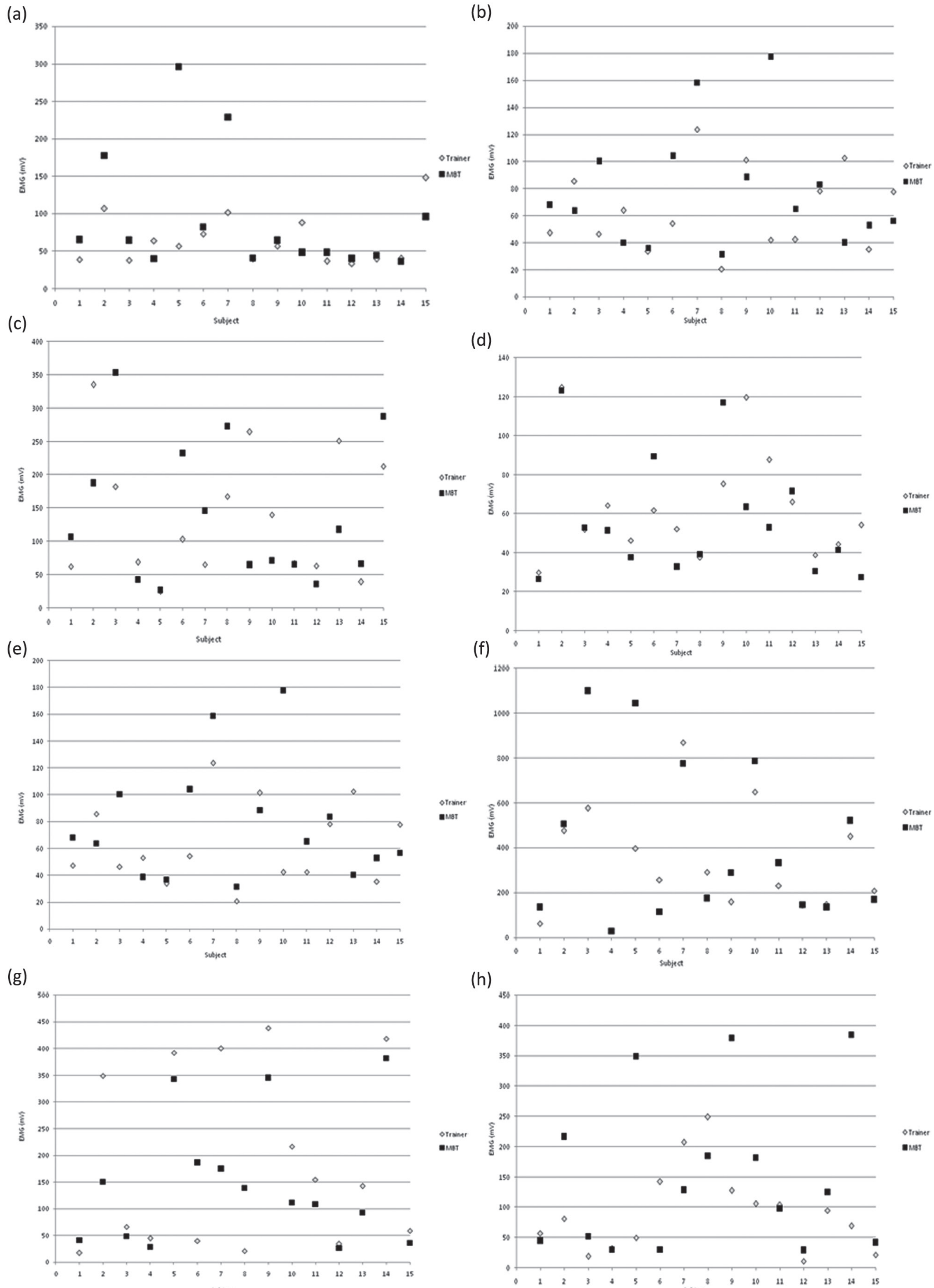

Figure 1. Scatter plot for the mean activity of each muscle for each subject in each shoe condition: (a) soleus, (b) medial gastrocnemius, (c) lateral gastrocnemius, (d) tibialis anterior, (e) peroneus longus, (f) rectus femoris, (g) biceps femoris and (h) gluteus medius. Triangle markers indicate the subjects own trainer shoe and the square markers indicate MBT shoes.
MBT: Masai Barefoot Technology; EMG: electromyography.

Table 2. The mean time (s) at which each event (HS, HL and TO) occurred during gait cycle for each condition.

Trainer shoe				MBT shoe		
Subject	HS	HL	TO	HS	HL	TO
1	0	0.08	0.95	0	0.07	0.8
2	0.02	0.15	0.99	0.029	0.13	0.98
3	0	0.42	0.42	0.1	0.47	0.47
4	0	0.41	0.41	0.007	0.42	0.42
5	0.01	0.08	0.65	0	0.05	0.61
6	0	0.48	0.79	0	0.62	0.71
7	0	0.3	0.6	0.01	0.28	0.59
8	0	0.32	0.66	0	0.44	0.85
9	0.1	0.22	0.62	0	0.19	0.6
10	0	0.25	0.59	0.007	0.12	0.57
11	0.007	0.11	0.59	0	0.02	0.58
12	0.009	0.23	0.61	0.009	0.23	0.61
13	0	0.17	0.66	0.012	0.08	0.6
14	0.006	0.08	0.34	0.02	0.15	0.54
15	0.01	0.06	0.63	0.013	0.013	0.64
Mean	0.025378	0.13751883	0.17743409	0.025321	0.18752709	0.14477569

MBT: Masai Barefoot Technology; HS: heel strike; HL: heel lift; TO: toe off.

altered weight rather than the design of the shoe. Advancing technology to developing varying levels and grades of instability shoes that can be personalised to the subject's needs and functions could provide differing levels of support and instability dependent on individual muscle activity giving more specific impact. This varied and staged approach will enable a choice as to the most suitable level of instability required.

Discreet changes in the number of footsteps taken, gait event timings and percentage of maximum EMG used were also noted from this study. Overall, the results for these outcomes were unremarkable and the differences between the trainer shoe and MBT shoe were negligible. A primary reason for this could be due to the design of the study where cadence and trainer shoe were not controlled. It was, however, noticed that in some of the subjects, the MBT shoe reduced the number of steps taken, and within that subgroup, the contact time from heel strike to heel lift was faster. These changes (although not directly measured in this study) would alter the stride length and speed at which the subject walked. It has been reported that wearing the MBT shoe did reduce the number of the footsteps taken, and although this change was seen in some of the subjects studied, the result was not constant across all subjects.[2] For a therapeutic intervention, a reduction in footsteps and altered stride length may be a desired outcome for management of certain conditions where the posterior group of muscles is strained, that is, hamstring injury and Achilles tendon pathology. Specific assessment and further research as to the suitability of using the unstable shoe for such an intervention would be required prior to the use of the shoe as a treatment modality.

The percentage of maximum that the mean value of muscle EMG activity worked at compared to the exercise one leg tip toe condition was not significant but indicated that each of the muscles studied demonstrated a mean EMG value of 30% for trainer shoe and 31.4% for MBT shoe. It can be argued that the MBT shoe, therefore, has little effect on the percentage of maximum work done by each of the muscles studied. Expanding this study to evaluate the prolonged changes over a time period when wearing MBT shoe would enhance the understanding of the effect that the unstable shoe has on EMG activity.

Although the results demonstrated variability between subjects, the muscle activation pattern from the MBT shoe condition was in synchrony with the normal trainer shoes suggesting that using MBT shoes do not alter the activation pattern but only alter the intensity of muscle activity when a change is observed. This outcome could be used therapeutically to implement a training effect for treatment of pathologies that are associated with underuse of a muscle. The MBT shoe could be used as a training device to be worn for a set period of time each day. Considering the unpredictable reaction seen within this group, thorough individual assessment of patient suitability would be required prior to intervention to evaluate the individual response to the use of MBT shoe. For those subjects who respond with an increase in muscle activity, the MBT shoe could then be used as a training device to improve poor muscle function. Further work is strongly recommended to investigate the therapeutic use of such shoes and the use of the MBT shoe in the management of pathologies associated to muscle fatigue, imbalance and dysfunction.

In view of the results produced from this study and other significant work on MBT shoes,[3,5,9] the widespread commercial availability of MBT and other unstable shoes should be monitored more closely as the effect of the shoe on function and stability can vary so greatly between subjects. It is not known if the immediate or long-term use of unstable shoes has an impact on health. A more vigorous method of assessment as to the suitability of wearing an unstable shoe is recommended. This will require additional understanding as to the effect unstable shoes have on whole body function and adaptation with a focus on identifying factors that predict the behaviour of muscles while subjected to an unstable environment.

Conclusion

This study has shown that there is an increase in mean muscle activity in lower limb muscles, specifically SOL, MG, PL, RF and GMed, but this increase is not statistically significant and varies greatly between subjects when walking in the MBT shoe for the first time without any prior training or muscle adaptation. Although this observed increase in muscle activity in the MBT unstable shoe can occur in some individuals, the mean muscle activity can equally decrease in others. The full effect of wearing such an unstable shoe is not yet fully revealed, and further work into the long-term use and therapeutic use of unstable shoes is recommended.

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Conflict of interest

None declared.

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Appendix 10

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The effect of shoe toe box shape and volume on forefoot interdigital and plantar pressures in healthy females

Helen Branthwaite[1*†], Nachiappan Chockalingam[1†] and Andrew Greenhalgh[1,2†]

Abstract

Background: Ill-fitting footwear can be detrimental to foot health with the forefoot being an area for most discomfort. Studies on footwear have primarily examined sports or orthopaedic prescription shoes and little is known about the effects that everyday flat shoes have on the forefoot. The aim of this study was to investigate the effect of toe box shape in a popular slip-on pump on dorsal and plantar pressures with particular interest around the forefoot in a healthy female population.

Method: A convenience sample of 27 female participants with no known foot pathologies was recruited. After assessment of foot size, plantar foot pressure and interdigital pressures were recorded for each of the 3 different toe box styles; round, square and pointed. Participants walked at a self-selected speed over a 10 m walkway whilst wearing each of the 3 styles of shoe and also whilst barefoot. Processed and analysed data extracted included peak pressure, time to peak pressure, contact time and pressure time integral. ANOVA and Freidman analysis was used to test for statistical significance.

Results: Shoes with a round toe showed least pressure around the medial aspect of the toes whilst the pointed shoe had least pressure on the lateral toes. Contact times for the plantar regions were not altered in any shoe condition yet contact around the medial aspect of the toes was highest in the pointed shoe.

Conclusion: This study highlights that the shape of the toe box in footwear can significantly influence the amount of pressure applied to the forefoot. Furthermore, the contours of the shoe also have an impact on the contact time and pressure time integral around the forefoot and also the peak plantar pressure in the toe region. The changes observed could be significant in the development of pathology in certain footwear toe box shapes. Consideration should be given to footwear design around the toe box to improve fit and reduce pressure. Further work is required to investigate the effect of toe box shape and volume on a pathological population with pressure related lesions.

Keywords: Foot pressure, Shoe shape, Digital pressure, Footwear, Toe box

Background

Analysis of the effects footwear has on foot function have previously focused on how changes in material composition, design of heel counter, sole stiffness and thickness and motion control alter whilst wearing the shoe [1-4]. This body of research has focused on running and athletic shoes and results have highlighted that a stiffer heel counter reduces rearfoot motion and improves comfort [5,6]. Sole stiffness and thickness alter stability and balance [7-9] and motion control has a varied impact on rearfoot kinematics [6,10]. However, running and athletic shoes are infrequently chosen by females for everyday use [11]. Current research suggests that footwear related pain in the general population is dominated by females who associate up to 60% of foot pain to the shoes that have been worn with the elderly female population reporting a high association between ill fitting footwear and foot pain [12].

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The concept of ill fitting footwear for females within published literature often leads to the assumption that joint pathologies and deformities are caused by wearing high heels. It is widely reported that the use of a heeled shoe for a prolonged time can have detrimental effects on foot health [13-15]. Studies investigating the effects of heel height have primarily focused on the influence of heel elevation on plantar pressure and triceps surae function rather than any other characteristics this shoe type imposes. Furthermore, these reported changes in increased forefoot pressure and altered triceps surae function do not directly identify the impact high heeled shoes have on toe deformities. Shoe toe box shape and volume may have a similar impact on foot health than the height of the heel. Reduced volume in the toe box causing cramping of the toes has been associated with foot deformities including the development of joint pathologies and forefoot lesions [12]. Hammer toe deformity where the interphalangeal joint is often prominent, may cause pain and callus due to irritation from shoe wear [16]. Increases in forefoot plantar pressure have been associated with the development of metatarsalgia, callus formation and increased risk of ulceration under the metatarsal heads [17-20]. Treatment of these lesions should provide symptomatic relief and alleviate the underlying mechanical cause yet continuation of ill fitting footwear will ensure these painful conditions persist [21].

Most soft tissue lesions can be managed conservatively by the use of shoes with a good fit and appropriate padding to redistribute pressure. Off loading pressure does in fact represent an indispensable precondition both for encouraging the tissue-repair mechanism, where active lesions are present, and for stopping the potential progression of pre-ulcerative conditions toward lesions. Previous studies indicate that for the site to be off loaded effectively, peak pressures needs to be below 99 N/cm^2 [22,23]. However, Pressure–time Integral is thought to have a greater role in lesion pathogenesis as the length of time that pressure is applied can be significant in the formation of pathology [20,24].

The forefoot has been highlighted as the most frequent area of pain in subjects who have foot pain related to footwear. Furthermore, subjects who had pain in the forefoot associated that pain with the footwear worn and had a significantly larger circumference of the foot than the subjects without any pain [12]. Other studies report similar findings around forefoot shape and fit, in particular the width fitting of shoes worn by two thirds of elderly females has been shown to be too narrow at the toe box [25,26]. This altered fit and disparity between forefoot shape and shoe volume are thought to significantly contribute to the development of toe deformities and the persistence of symptoms that require clinical intervention [27]. Changes in footwear from narrow fitting shoes to a broader walker style have shown to reduce the incidence of foot pain [28]. Education on the ill-effects of tight fitting footwear is poor and research indicates that footwear in the younger population is influenced by fashion and colour [29,30]. Footwear choice in young females is determined by the activity that is planned with high heels being chosen for socialising, boots for warmth and flat ballet pumps for school [11].

This study aimed to investigate differences in toe box volume and shape with a particular focus on peak pressure, time to peak pressure, total contact time and pressure time integral around the dorsal aspect of the forefoot and defined plantar foot regions in a healthy young female population with no known foot pathology.

Methods

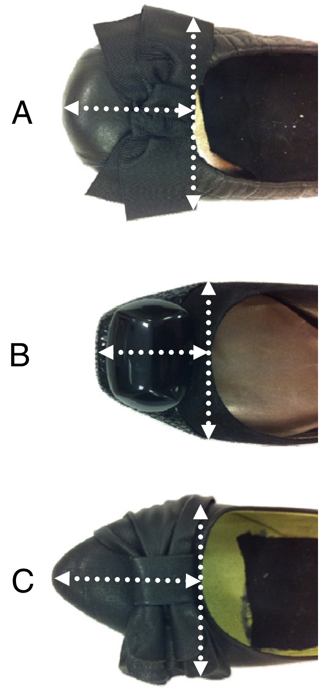
Participants

27 asymptomatic healthy females were recruited from a convenience sample with an average age of 22.5 (+/− 4.5) years, body mass of 63.3 (+/− 8.9) kg, height of 1.64 (+/− 0. 6.5) m, shoe size UK 5.5 (+/− 0.8). All recruited subjects gave full consent to participate in the study. Ethical approval was sought and granted from Staffordshire University ethics committee. All subjects included in the study were asymptomatic at the time of testing and were excluded if any musculoskeletal foot pathologies were present, particularly in the forefoot for example: hallux valgus, lesser toe deformities and fifth metatarsophalangeal joint deformities.

Foot sizing measurements for foot length were taken using a Brannock device® to match the foot tested with the appropriate footwear size. A subjective assessment for footwear fitting and comfort was conducted for each subject prior to testing in that shoe. Three types of footwear were used within this study. The key difference in the 3 footwear styles tested was the shape and dimensions of the toe box: square, round and pointed toe (Figure 1). Colour and design were controlled by including black ballet pumps with an accessory feature on the toe box. Subjects were blinded to the brand of the footwear by removing all labelling. Sole thickness and material were assessed and closely matched, however differences in sole material were present. The volume of each shoe's toe box was measured by calculating the average quantity of fine sand that filled the shoe to a level where the toe box upper finished (Figure 1).

Data collection

Plantar foot pressure was measured for each shoe condition as well as a barefoot condition using a 1 m pressure plate (Footscan®, RsScan Olen, Belgium). The plate was built into the walkway and placed 4 m along a total length of 10 m. This enabled the subjects to attain a normalised walking speed prior to data capture and prevent



Size	Toe box	Round A	Square B	Point C
4	Volume	36	47	44
	Width	7.4	7.6	7.5
	Depth	3.8	4.5	6.5
5	Volume	45	55	60
	Width	7.6	8.0	7.7
	Depth	4.1	5.0	7.0
6	Volume	50	60	60
	Width	7.9	8.2	8.0
	Depth	4.2	4.9	7.0
7	Volume	54	73	68
	Width	8.3	8.5	8.2
	Depth	4.9	5.4	7.0

Figure 1 Three toe box shapes, (A) round, (B) square and (C) pointed. All shoes were a slip on flat pump. The volume of each shoe was measured using the indicated shoe width and upper for definition of toe box, highlighted by white arrows. The table indicates the volume (cm^3), width and depth (cm) of the toe box for each shoe size tested.

stepping onto the plate [31]. The plate was calibrated to each individual participant's body weight prior to data collection. Each condition was tested in a randomised order determined prior to data collection with subjects choosing a folded card identifying the order of the test condition. There were two successful walking trials collected for barefoot, square shoe, round shoe and pointed shoes.

Interdigital and dorsal pressure was collected separately using Walkinsense® (Tomorrow Options Microelectronics, Portugal). See Figures 2 and 3. This new system allows for individual sensors to be located anywhere on the foot and has been previously validated [32]. Eight piezoresistive force 100Hz sensors were individually secured with adhesive tape (Micropore™) to the following landmarks (Figure 3):

(i) medial border of the 1st metatarsophalangeal joint,
(ii) medial border of the 1st interphalangeal joint,
(iii) interdigital (1/2, 2/3, 3/4, 4/5)
(iv) proximal interphalangeal joint,
(v) 5th proximal interphalangeal joint
(vi) lateral border of the 5th metatarsal head

Footwear was tested in the same randomised order as the plantar pressure and data were collected from self selected walking speed over a 10 m walkway. Barefoot data was not captured for interdigital and dorsal pressures as recorded data is only captured whilst pressure is exerted on the sensor. Data was captured for a whole gait cycle and the overall pressure was analysed from footstep 3 and 6, these were identified to represent normal walking [33].

Data processing and analysis

Plantar pressure data from the pressure platform and dorsal and interdigital pressure data from sensor placement pressure measurement system were averaged and processed to obtain the following measures: peak pressure, time to peak pressure, contact time and pressure time integral. These measures were assessed for each of the 8 individual sensors and for the 10 anatomical areas of the plantar pressure recording (heel lateral, heel medial, midfoot, metatarsal 1,2,3,4 and 5, 1st digit and toes 2–5) [34].

Processed data was then statistically analysed using SPSS ver.19 (IBM, USA). Each data set was assessed for normalcy and those test conditions meeting all parametric assumptions were statistically analysed using a one way repeated measures analysis of variance (ANOVA). Test conditions that failed to meet all assumptions for parametric testing were analysed using the non parametric alternative Freidman Test with significant results being further analysed with a post hoc Wilcoxon Signed Rank Test with a Bonferroni adjusted alpha value.

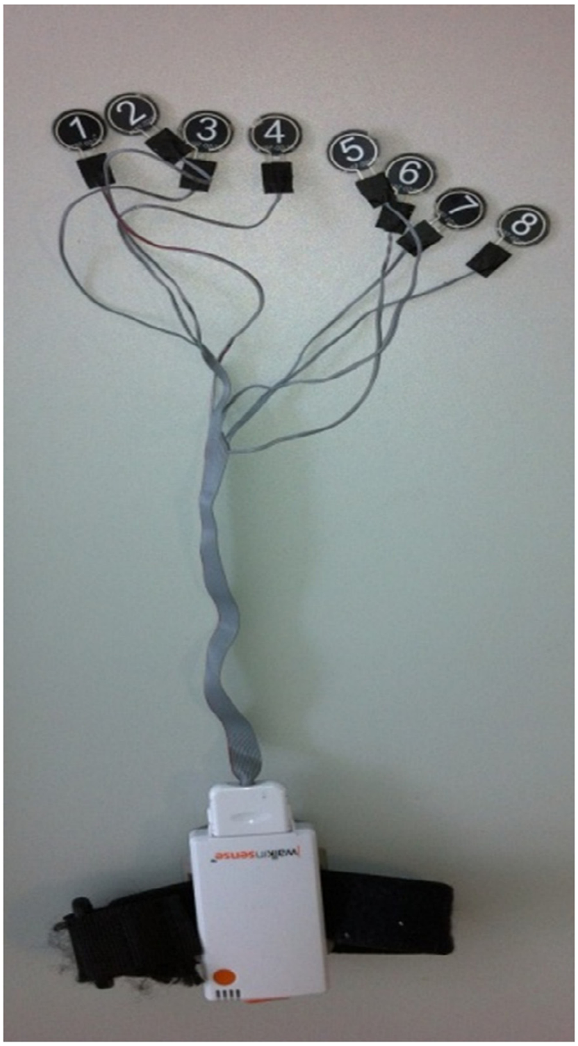


Figure 2 Walkinsense equipment. Sensors are 1 cm^2 and <1 mm thick.

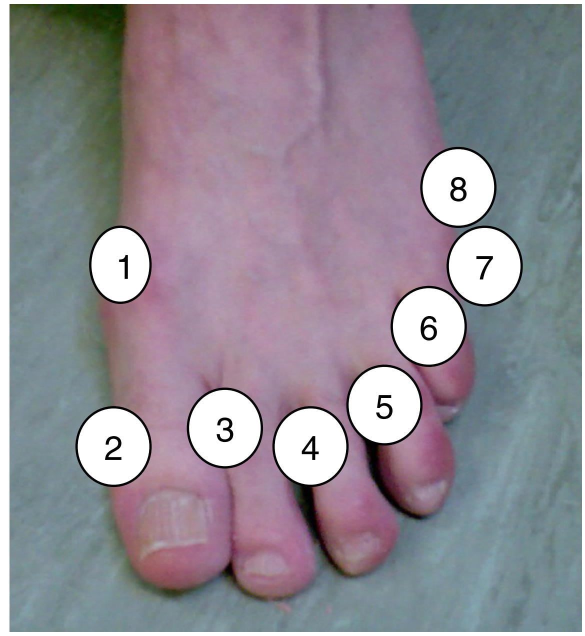


Figure 3 Sensor placement 1–8 starting at the medial aspect of the 1st metatarsophalangeal joint and finishing on the lateral aspect of the foot at the 5th metatarsophalangeal joint.

Results

The volume for each shoe tested varied between style and size (Figure 1). The round shoe shape had the least volume in the toe box across all sizes and the square toed shoe had the highest volume except in size 5.

Peak pressure

Statistical tests showed a significant difference between shoe conditions for peak pressure at sensor 1, 2, 3, 4, 7 and 8 with the round shoe condition producing the least amount of pressure for sensor 1, 2, 3, 4 and 8. The pointed shoe applied the least pressure over sensor 6 and 7 which were applied on the fifth digit, with the square shoe producing the most pressure over this digit. Mean plantar peak pressure was significantly different across all masked areas of the foot with the exception of the second metatarsal where no difference was observed. Pointed shoes demonstrated the highest peak plantar pressure at the medial heel yet this shoe condition was the lowest pressure value for the toe regions (Tables 1 and 2).

Time to peak pressure

Results from sensors 2, 4, 5 and 8 demonstrated significant differences, with the round shoe condition demonstrating an earlier time to peak pressure in all 8 sensors. Plantar foot regions demonstrated exhibited similar time to peak pressure in all of the masked regions however there was a significant difference between the barefoot condition and all shoe conditions (Tables 1 and 2).

Contact time

Sensors 2, 3, 4 and 5 and the toe regions showed significant differences in contact time, whilst all other sensors and plantar foot regions showed no differences between shoe shape and barefoot conditions. The square shaped shoe and pointed shoe was where the significance fell with a pointed shoe being in contact with the foot for longer periods of time on the dorsal aspect of the foot and the square shoe being in contact with the toes two - five in the plantar aspect of the foot.

Pressure time integral

Sensors 2, 3, 4 and 8 showed variable significant differences between the pointed shoe having a higher pressure time integral at 2, 3 and 4 and the round shoe being significantly lower at sensor 8. The midfoot region, first toe

Table 1 Interdigital and dorsal pressure results – mean (SD)

	Round	Square	Point	*p* value
Mean peak pressure (N/cm^2)				
Sensor 1	40.2(0.31) ‡	57.85(0.34)	51.97(0.43)	0.017*
Sensor 2	16.67(0.24)§	47.07(0.57)	48.05(0.47)	0.001*
Sensor 3	22.55(0.34) ‡§	32.36(0.42)	39.22(0.48)	0.005**
Sensor 4	25.49(0.36) ‡§	43.15(0.44)	45.11(0.44)	0.000*
Sensor 5	30.4(0.42)	38.24(0.41)	32.36(0.4)	0.134**
Sensor 6	57.85(0.45)	65.7(0.54)	50.01(0.37)	0.273*
Sensor 7	73.54(0.47)§	89.23(0.51)	60.8(0.43)	0.001*
Sensor 8	34.32(0.29) ‡§	57.85(0.3)†§	83.35(0.44)†‡	0.000*
Mean time to peak pressure (ms)				
Sensor 1	190(0.19)	290(0.19)	260(0.19)	0.194*
Sensor 2	80(0.15)§	160(0.19)	300(0.25)	0.011*
Sensor 3	150(0.21)	180(0.21)	230(0.23)	0.6**
Sensor 4	110(0.14)§	190(0.17)	270(0.21)	0.008*
Sensor 5	160(0.17)‡§	250(0.21)	240(0.2)	0.004**
Sensor 6	300(0.17)	340(0.19)	360(0.52)	0.038*
Sensor 7	280(0.13)	330(0.14)	290(0.15)	0.037*
Sensor 8	190(0.12)‡§	300(0.13)	340(0.14)	0.000*
Mean total contact time (ms)				
Sensor 1	610(0.36)	690(0.27)	640(0.19)	0.544*
Sensor 2	210(0.3)	210(0.23)§	450(0.36)	0.003*
Sensor 3	220(0.26)‡§	300(0.31)†§	490(0.74)†‡	0.003**
Sensor 4	300(0.36)	260(0.21)§	450(0.33)	0.009*
Sensor 5	350(0.35)	430(0.38)	560(0.31)†	0.029**
Sensor 6	590(0.33)	550(0.32)	590(0.67)	0.664*
Sensor 7	520(0.24)	520(0.19)	510(0.23)	0.893*
Sensor 8	420(0.24)	510(0.2)	540(0.19)	0.34*
Pressure–time integral (N/cm^2/ms)				
Sensor 1	15.54(17.01)	19.53(17.22)	17.06(19.54)	0.133*
Sensor 2	1.17(2.7)	6.32(10.64)	10.62(14.62)†‡	0.001*
Sensor 3	3.24(6.97)‡§	5.25(10.4)	8.64(14.33)	0.001**
Sensor 4	3.59(7.45)	7.01(10.27)	9.38(12.79)†	0.001*
Sensor 5	7.07(13.83)	8.35(11.92)	9.23(15.76)	0.31**
Sensor 6	16.41(17.77)	18.5(23.1)	10.9(11.88)	0.56*
Sensor 7	17.97(18.87)	23.09(21.98)	15.7(18.13)	0.145*
Sensor 8	7.63(8.59)‡	14.41(11.62)§	18.45(16.19)	0.000*

* ANOVA.
** Friedman test.
† significantly different to round.
‡ significantly different to square.
§ significantly different to point.

and toes –2-5 were areas that also showed a significant difference between conditions, with variance lying between the pointed shoe at the midfoot (having a significant lower pressure time integral than the other conditions) and the square shoe conditions. The barefoot condition had a higher pressure time integral around the plantar region of the toes 2–5.

Discussion

The results of this study clearly indicate that the shape of a shoe's toe box has a significant impact on dorsal and plantar pressures of the foot. Round toe shoes were shown to produce less peak pressure around the medial aspect of the foot, and the pressure time integral is also lower in this region. Conversely, the pointed style of shoe distributed

Table 2 Plantar pressure results – mean (SD)

	Barefoot	Round	Square	Point	*p* value
Mean peak pressure (N/cm^2)					
Heel – medial	19.29(7.42)§	23.81(9.56)§	22.47(11.09)§	38.36(8.24)	0.000*
Heel – lateral	16.71(5.14)‡§	17.45(7.08)‡§	24.9(7.45)†§	32.21(7.92)†‡	0.000*
Midfoot	8.35(5.36)†§	6.75(2.49)	8.29(4.01)	3.28(1.87)	0.000*
Metatarsal head 1	19.06(8.54)†‡§	17.98(6.53)	15.05(5.93)	10.01(6.49)	0.000*
Metatarsal head 2	18.11(10.97)	18.89(10.23)	20.06(7.79)	21.79(8.23)	0.195*
Metatarsal head 3	17.16(9.3)†§	18.85(11.7)	19.47(6.31)	24.06(10.61)	0.005*
Metatarsal head 4	17.79(7.57)†§	23.99(12.99)‡§	11.6(4)†§	14.32(5.84)†‡	0.000*
Metatarsal head 5	7.53(6.14)‡§	16.67(12.74)‡§	9.28(4.97)	5.41(2.99)	0.000*
Toe 1	24.4(18.8)	24.66(15.35)	12.27(6.28)§	10.77(6.04)	0.000**
Toes 2-5	11.53(15.45)‡§	15.78(15.09)	5.92(7.37)†§	2.63(2.48)	0.000**
Mean time to peak pressure (ms)					
Heel – medial	136.29(31.59)	139.4(97.94)	133.5(75.69)	115.63(64.6)†§	0.000*
Heel – lateral	126.71(41.41)‡§	129.67(62.78)‡§	144.91(85.3)†§	140.23(68.54)†‡	0.000*
Midfoot	234.9(63.92)†‡	290.98(97.43)	320.67(83.24)	234.51(66.64)	0.000*
Metatarsal head 1	490.82(139.71)†‡	524.37(113.83)	512.25(67.26)	486.85(51.09)	0.000*
Metatarsal head 2	516.9(109.73)	515.53(109.21)	517.72(61.9)	517.59(45.53)	0.08*
Metatarsal head 3	497.34(108.83)†	510.81(104.8)	479.37(66.1)	506.85(52.53)	0.002*
Metatarsal head 4	452.06(11.45)†‡	462.91(104.35)	448.29(75.16)	471.97(67.76)†‡	0.001*
Metatarsal head 5	350.09(174.91)‡§	368.74(114.85)‡	404.17(85.18)	402.79(92.98)	0.000*
Toe 1	595.71(116.74)†	613.24(125.25)	525.59(144.43)	539.71(70.58)	0.006**
Toes 2-5	552.94(98.03)§	490.09(179.56)	480.1(143.19)§	510.43(93.12)	0.026**
Mean total contact time (ms)					
Heel – medial	371.8(64.32)	410.31(106.4)	394.5(74.82)	387.83(68.15)	0.36*
Heel – lateral	365.9(62.3)	383.87(90.66)	395.04(77.02)	387.89(61.1)	0.109*
Midfoot	404.1(65.24)	421.81(82.7)	424.4(67.3)	388.54(79.95)	0.08*
Metatarsal head 1	491.3(112.34)	485.9(79.21)	479.26(84.9)	486.84(51.09)	0.42*
Metatarsal head 2	504.25(136.3)	514.5(108.83)	489.79(112.26)	518(69.69)	0.52*
Metatarsal head 3	533.74(106.8)	508.4(137.4)	525.09(62.56)	537.86(68.17)	0.24*
Metatarsal head 4	522.72(139.9)	547.2(106.3)	518.58(53.55)	540.45(56.58)	0.188*
Metatarsal head 5	502.61(96.28)	492.71(140.8)	484.95(82.6)	478.84(63.91)	0.79*
Toe 1	299.4(83.75)†§	248.72(71.94)	279(115.1)	392.48(116.45)	0.000**
Toes 2-5	419.94(208.46)†§	310.47(182.6)	453.87(214)§	281.64(99.52)	0.003**
Pressure–time integral (N/cm^2/ms)					
Heel – medial	4.24(1.84)	5.35(2.31)	4.8(2.37)	8.38(2.91)	0.309*
Heel – lateral	3.58(1.26)	3.68(1.37)	5.42(1.71)	7.26(2.24)	0.642*
Midfoot	2.01(1.42)†§	1.73(0.77)	2.19(1.07)	0.78(0.51)	0.000*
Metatarsal head 1	3.99(1.58)	3.71(1.58)	3.24(1.54)	2.17(1.55)	0.043*
Metatarsal head 2	4.27(2.79)	3.99(2.35)	4.31(2.02)	5.1(2.07)	0.999*
Metatarsal head 3	4.04(2.11)	4.37(3.25)	4.97(1.95)	5.91(3.22)	0.06*

Table 2 Plantar pressure results – mean (SD) *(Continued)*

Metatarsal head 4	5.18(2.66)	6.59(4.23)	2.97(1.15)	3.78(1.91)	0.396*
Metatarsal head 5	2.18(2.04)	2.32(3.39)	2.54(1.52)	1.31(0.85)	0.462*
Toe 1	3.08(2.39)‡§	2.67(1.64)	1.24(0.82)	1.76(1.11)	0.001**
Toes 2-5	1.37(1.38)	1.48(1.57)	4.09(1.18)†§	0.37(0.33)	0.002**

* ANOVA.
** Friedman test.
† significantly different to round.
‡ significantly different to square.
§ significantly different to point.

the least amount of pressure in the lateral toe area. These observations can be related directly to the dimension and shaping of each the round and pointed shoe styles which correlate to the natural anatomical contours of the foot. However, the volume of the shoe was not correlated to forefoot pressure, with the round shoe having the least volume in the toe box across all shoe sizes tested and this condition demonstrated the lowest pressure values. This lack of correlation might be due to the stylised point of the shoe. This pointed shoe has an extended length to the normal foot contour, which increases the measured volume but does not alter the toe pressure due to lack of direct contact. The shape of the toe box therefore should be considered as a cause of increased forefoot pressure and not just the width of the shoe as previously mentioned as a problematic design of ill-fitting footwear [12,25,26].

The dorsal digital area showed higher peak pressure on the medial side of the foot whilst wearing a square and pointed shoe shape, with the design of the shoes encroaching on the natural shape of the first digit. Similarly this correlation of shoe shape and foot shape was also seen in the square toed shoe which exerted the highest amount of peak pressure over the fifth digit. The gradient of the lateral border of the toe box was similar both in the square shaped and the pointed shoe. There was greater variability regarding regional significance of peak plantar pressure in the masked areas of the plantar pressure with each shoe condition showing significance at different regions of the foot. The sole material of each shoe was not controlled within the study design and will have altered plantar pressure distribution and results. Although care was taken to choose three designs that only differed by toe box shape it was difficult to replicate the same sole characteristics. However, the round shoe shape did consistently result in higher peak plantar pressure within the forefoot region accompanied by lower dorsal peak pressures around the medial forefoot. This could be due to a lower recorded volume of the toe box and possible cramping of the normal toe profile altering toe function and plantar pressure during toe off.

It is also worth highlighting that the pointed shoe condition produced a significantly higher peak plantar pressure at the medial heel region than then other shoes. The pointed shoe that was tested had a more flexible heel counter compared to the other two shoe conditions, this feature had not be controlled for, which could possibly explain the increased medial heel pressure due to lack of structure.

The time to reach peak plantar pressure differed only at the masked toe region with all shoe conditions reducing the time to peak pressure compared to the barefoot condition. The contact time for this region was also lower for all shoe conditions excluding the shoes with a square toe which resembled the barefoot condition. This could be due to the stiffness of the sole of the shoe rather than the shape of the toe box which resulted in the toe area having reduced contact. The dorsal aspect of the foot around the fifth metatarsal and the first digit were most different when wearing the pointed shoe with increased time to peak pressure and contact in these regions. This shoe shape intensifies pressure over the border of the forefoot due to its angular shape.

There were significant differences between footwear conditions when analysing the pressure time integral data, which has been identified as significant when considering chronic tissue strain in the formation of callus and other hyperkeratotic skin lesions [20,24]. The lateral border of the foot around the fifth metatarsal and digit exhibited the greatest differences when wearing the pointed shoe with a lower pressure time integral. The square shoe condition had the highest pressure time integral around this area. The fit of the foot in this style of shoe due to its dimension and the lack of control for heel to ball of foot measure could have induced this higher result with the alignment of the toes differing between participants.

Clinical presentation of hyperkeratotic skin lesions around the 5th digit could therefore be due to the shape of the shoe toe box rather than the perception of whether the shoe is a good fit or not. For example, a well supported lace up shoe with a pointed or square toe box may cause lateral irritation to the foot even though it is deemed a good fit elsewhere.

The results of this study did not exceed the reported peak pressure values of over 99Ncm^2, which have been acknowledged to be the threshold for tissue damage

[22,23]. The recorded forefoot pressures studied were purposefully from a sample with no known pathological foot problems to gather pre-pathology data. The inclusion of toe deformities and forefoot pain may present with differing results. There is, however, a lack of information to define what quantity of pressure is required to develop chronic responses to mechanical strain with the common formation of hyperkeratotic callus, and further studies into this area are recommended.

The fifth toe and interdigital fourth and fifth area are common locations to develop focal chronic callus lesions. The results from this study suggest that the shape of the toe box may play a part in the development of such lesions with the lateral border of the forefoot resulting in higher peak pressure and pressure time integrals in the square shoe. An increase in pressure may be attributed to the graduation of the toe box shape if does not follow the anatomy of the foot. Changes to footwear style may help to reduce the incidence of these common problems and improve comfort for many females. Cases have been reported where the fifth digit has been amputated to accommodate the foot in a desired shoe [35]. Further research into the impact of footwear styling at the toe box on pathological feet is recommended.

Considering the results from this study, development of shoe design needs to advance to encompass an accepted toe box for fashion as well as foot health. This may involve the medial border of the shoe around the 1st metarsalphalangeal joint and the first toe being designed in a round shape and the lateral border around the 5th interphalangeal joint having a pointed graduated shape. These style features could minimise peak pressure, contact times and consequently pressure time integral in the forefoot. This style and shape of shoe is infrequently seen in the market place with the majority of footwear styles adopting a narrowed toe box with equal shaping to the medial and lateral side of the shoe. By limiting consumer choices on footwear shape people are forced to choose footwear that has been shown to alter pressure to the forefoot. Providing footwear choices that do not impact on forefoot pressure could prevent pathologies that are associated with ill fitting shoes.

There are limited studies to investigate the impact that footwear shape and style have on foot pathologies however, there are strong links between foot pain and ill fitting footwear especially in the elderly population [36]. Footwear choices are led by fashion and image rather than health [11,29,30]. Changes in footwear design for younger adults, to accommodate natural foot position and shape, may be a useful way to help prevent painful foot pathologies and deformities occurring prior to old age.

The style of footwear investigated in this study was determined by fashion and the most popular choice amongst young females [11]. Although, the fit of the foot in the shoe around the toe box may alter with increased heel height, fastening of the shoe, shoe upper material and also last shape, the conclusions outlined in this manuscript do not address these factors. Further structured investigation into quantifying the pressure under the upper is required. Furthermore, there should be a detailed examination of all shoe styles with varied toe box shapes. The pointed shoe employed within this investigation was longer in the toe box region than the square and round shoe and therefore had an increased volume. The styled extension of this toe box may have masked the actual fit of the foot inside the shoe. This might require further scientific study of the relationship between design and function. In addition to this, studying a population with foot pathology will help in understanding the contribution footwear style makes to development of foot disorders.

Conclusion

The shape of the toe box can alter the pressure applied to the forefoot around the digits and plantar aspect of the foot in healthy young women with no known foot pathology. Hence, footwear advice with reference to the shape of the toe box is essential in the management of pressure related lesions and when preventative measures are being considered.

Competing interests

All authors involved in this manuscript can declare that they had no competing interests.

Authors' contributions

HB led this study and was involved in the study design, data collection and extraction including statistical analysis and prepared this manuscript. AG wrote the code to extract and process all the raw data. NC was involved in the design of the study and the preparation of the manuscript. All authors reviewed and agreed on the final manuscript before submission.

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Appendix 11

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The effect of footwear design on interdigital and plantar pressures

Background: The effects of ill fitting footwear can be detrimental to foot health with the forefoot being an area for most discomfort. Studies on footwear primarily look at sports shoes or orthopaedic prescription shoes and little is known about the effect everyday flat shoes have on the forefoot. The overall aim of this study was to investigate the effect of toe box shape in commercially available popular slip on pumps on dorsal and plantar pressures with particular interest around the forefoot.

Methodology: A repeated measure study design was implemented. 27 female participants with no known foot pathologies were recruited from a convenience sample of students (age 22.5 (± 4.5) years, body mass of 63.3 (± 8.9) kg, and height of 1.64 (±0. 6.5)m, shoe size UK 5.5 (± 0.8). Foot sizing measurements were taken using a Brannock device® and the appropriate measured footwear size was allocated to each subject. Three styles of ballet pump shoes were tested varying only in the shape of the toe box. The three variables in shape were square, round and pointed. Data was collected for plantar pressure using a 1 metre plate (Footscan, RsScan Olen, Belgium) interdigital pressure was captured using 8 individual piezoresistive force 100Hz sensors placed on the medial aspect of the 1st metatarsal phalangeal joint, medial 1st interphalangeal joint, interdigital on the distal phalanx of 1&2 2&3 3&4 4&5, lateral on the 5th interphalangeal joint and 5th metatarsal phalangeal joint (Walkinsense, Tomorrow Options Microelectronics, Portugal). Each subject was randomly assigned a footwear condition and on fitting the correct shoe walked along a designated 10m walkway with the pressure plate built in. Collected data was processed to gain the average of 3 footsteps and the following outcome measures, peak pressure, time to peak pressure, contact time and pressure time integral were extracted for each of the 8 sensors and 10 anatomical areas of the plantar pressure recording (heel lateral, heel medial, midfoot,metatarsal 1,2,3,4 and 5, 1st digit and toes2-5)(Naemi et al 2012). Each data set was assessed for normalcy and those test conditions meeting all parametric assumptions were statistically analysed using a one way repeated measures ANOVA (p.>0.05). Test conditions that failed to meet all assumptions for parametric testing were analysed using the non parametric alternative Freidman Test (p.>0.05) with significant results being further analysed with a post hoc Wilcoxon Signed Rank Test (p.>0.05) with a Bonferroni adjusted alpha value.

Results: Shoes with a round toe box shape showed least pressure around the medial aspect of the toes whilst the pointed shape shoe had least pressure on the lateral toes. Contact times for the plantar regions were not altered in any

shoe condition yet contact around the medial aspect of the toes was highest in the pointed shoe.

Conclusion: This study highlights that the footwear shape in the toe box region significantly alters the magnitude of pressure recorded around the toes. Furthermore, the contours of the shoe also have an impact on the plantar pressure and contact time. Further work investigating the effect of shoe shape on a population with pressure related lesions on the toes and medial and lateral aspects of the foot will demonstrate the impact shoe shape has on foot health

Appendix 12

The relationship between stiffness and comfort in casual ballet pump shoes.- A pilot study.

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Introduction

Comfort of a running shoe has been associated with cushioning, support and foot and leg alignment (Mündermann *et al*. 2001) Fit, foot bed shape, nature of activity and mobility have been identified as related to comfort in orthopaedic shoes and court shoes (Williams and Nester. 2006, Witana *et al*. 2009). Ballet pump shoes however are worn as everyday shoes by young females (Branthwaite *et al*. 2012) and the impact of comfort and footwear characteristics has not been investigated in this style of shoe. Running shoe bending stiffness has shown to be insignificant in the forefoot and the stiffness of the foot determines running performance (Oleson *et al.* 2005). However, stiff soled shoes are frequently used to improve pain in the forefoot (Smith *et al.* 2000).

Purpose of the Study

The purpose of this study was to investigate the relationship between the perceived comfort of a casual ballet pump shoe and the bending stiffness recorded.

Method

27 females age 22years (SD+/- 4.5), 63.3kg (SD+/-8.9), 164.4 cm(SD+/- 6.35) were recruited from a convenience sample of students. Ethical approval was sought and provided by the University Ethics Committee. Comfort of 3 popular ballet pump shoes were assessed using a 15cm visual analogue scale which ranged from not at all comfortable to extreme comfort. A comfort score was generated from 9 statements about the shoe. A maximum score of 135 indicated extreme comfort and values toward zero highlighted less comfort. The shoes (A,B,C) tested were the same colour style and design; brand was blinded to prevent bias. However, the sole material and apparent stiffness were different for each shoe.

Subjects wore each shoe in a randomised order for 5 minutes whilst walking at a self selected speed in a circular motion around a designated laboratory walkway. Comfort for each shoe was recorded in-between shoe conditions.

Cantilever bending tests (24 in total) were performed to assess shoe bending stiffness (Oleson *et al.* 2005). The specimens were clamped to a custom made rigid last and loaded at the plantar side with an extension rate of 2.5 mm/sec (Fig. 1). The distance between the bending axis and the loading axis was 40 mm. The displacement of the piston and the applied force were recorded at 100 Hz and the values of bending angle and moment were calculated. The initial stiffness (i.e. the initial slope of the moment / angle curve) as well as the work input (i.e. the area under the moment / angle curve) was calculated for each specimen. Statistical significance for bending stiffness was assessed with one way ANOVA and Spearmans rank correlation for comfort and stiffness (level of statistical significance P<0.05)

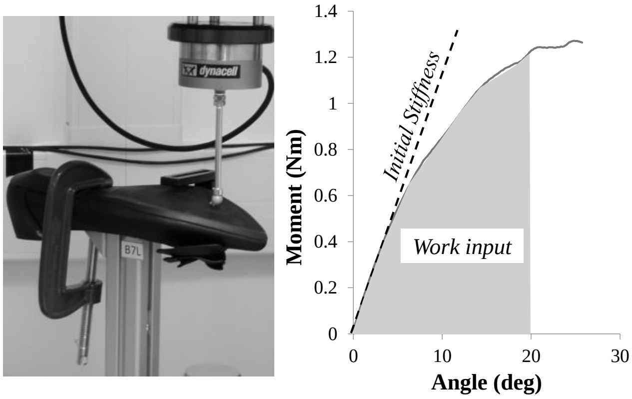

Figure 1. The experimental set up (left). A typical bending moment / angle curve (right).

Results

Spearmans rho (0.48) was significant (p=0.025) when correlating the bending stiffness of shoe C to the forefoot comfort score

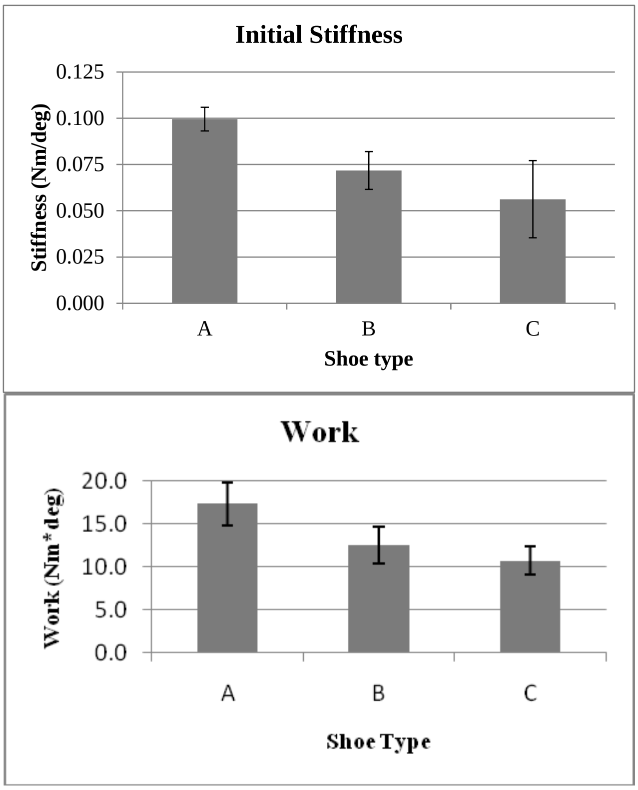

Figure 2. Comparison between the average values of initial stiffness (up) and work input (down) for the three different types of shoes.

Discussion and Conclusion

A series of cantilever bending tests indicated that shoe type A is significantly stiffer that B and C. Correlations between stiffness and comfort indicated that the more comfortable a shoe is at the forefoot the less stiff the sole is for bending. The study group were healthy individuals with no pain in the forefoot, stiffness in the shoe is used to restrict forefoot bending in painful metatarsals (Smith *et al* 2000) however this may not always be comfortable.

The results from this pilot study can be used to inform larger studies into the characteristics of everyday shoes and the effects sole stiffness has on comfort and function.

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Appendix 13

The reported effects and clinical uses of wearing and unstable shoe

Society of Chiropodists and Podiatrists Conference. 2013

This key note lecture was given to an audience of 200 Podiatrists during the annual Society of Chiropodists and Podiatrists conference in Liverpool UK. The themed group of lectures were organised by the working group on musculoskeletal dysfunction within the College of Podiatry.

The presentation covered the different types of unstable shoe available on the market and the reported effects of these shoes both from a marketing point of view and also a scientific opinion. From this introduction the focus then turned to reported effects of wearing the variety of shoes and how the proposed mechanisms could work to alter patient symptoms.

A fruitful discussion followed with several individuals sharing experiences of using the shoes for themselves as well as in the management of patient care.

The full power point presentation can be viewed on request if required. Below are a number of the key slides to demonstrate the type of literature presented.

Reported effects Science

MBT

No significant difference in balance Ramstrand et al 2010 Clin Biomech

Increased variability in kinematics prior to training which levels out after training. Stoggl et al 2010 Clin Biomech

Alters ankle kinematics and kinetics Boyer et al 2009 Clin Biomech

Increases forefoot pressure by 76% Stewart et al 2007 Gait and Postture

Reduced medial knee compartment loads in overweight males Bucheker et al 2010 Scand J Med Sci Sports

The Society of Chiropodists and Podiatrists

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Clinical use

- APOS knee OA
- No current literature to support use of MBT and Easy tone in pathology however :
  - Off loading at heel
    - Plantar fasciitis, achilles tendon pathology
  - Improve balance
  - Introduce variability

  - FURTHER clinical trials need to be completed

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Discussion

- The evidence to support the effects is varied and in some people positive changes occur, others nothing happens and then some people have negative effects.
- Instability shoes used as a training device.
- Availability of shoes should they be monitored closely?

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- Stewart et al 2007 Gait Posture
- Price et al 2013 Gait Posture
- Elkjaer et al 201115th Nordic Baltic conf
- Horsak and Baca 2013 Clin Biomech
- Bar-Ziv et al 2007 OA Cartilage

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Appendix 14

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The impact of different footwear characteristics, of a ballet flat pump, on centre of pressure progression and perceived comfort

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ABSTRACT

Background: Uncomfortable shoes have been attributed to poor fit and the cause of foot pathologies. Assessing and evaluating comfort and fit have proven challenging due to the subjective nature. The aim of this paper is to investigate the relationship between footwear characteristics and perceived comfort.
Methods: Twenty-seven females assessed three different styles of ballet pump shoe for comfort using a comfort scale whilst walking along a 20 m walkway. The physical characteristics of the shoes and the progression of centre of pressure during walking were assessed.
Results: There were significant physical differences between each style, square shoe being the shortest, widest and stiffest and round shoe having the least volume at the toe box. Centre of pressure progression angle was centralised to the longitudinal axis of the foot when wearing each of the three shoes compared to barefoot. Length, width and cantilever bending stiffness had no impact on perceived comfort.
Conclusion: Wearing snug fitting flexible soled round ballet flat pump is perceived to be the most comfortable of the shoe shapes tested producing a faster more efficient gait. Further investigations are required to assess impact/fit and upper material on perceived comfort to aid consumers with painful feet in purchasing shoes.

1. Introduction

The perceived comfort of a shoe may vary across individuals with multiple physical factors being reported as important, such as material properties [1], shoe fit [2], skeletal alignment [3] and fashion [4]. The specific conditions that define a comfortable shoe and therefore good fit are not clear but the most frequent and significant findings for shoe comfort have been attributed to (1) a feeling of support from the upper, (2) foot-bed contact with the foot and (3) stability of the shoe as a whole [5]. Deviations away from any of these parameters may play a considerable role in influencing the perceived comfort level of the shoe, which, has been shown to be considered as a significant factor when purchasing new shoes [11].

Uncomfortable shoes are often attributed to the cause of foot pain and pathology with 60% of female subjects experiencing foot pain related to the shoes worn. Previous research indicates that the most frequent area of discomfort and pain is around the toes, with the population studied having a greater circumference of the metatarsal heads associated to pain [6]. A shoe that is either too loose or too tight can also influence comfort with tissue compression in a snug shoe and slippage or friction in a larger shoe [4]. Observations on shoe wearing habits in the elderly indicates that up to 72% wear shoes that are ill-fitting associated to foot pain and ulceration [7]. Despite the strong evidence to support the notion that ill-fitting footwear can cause foot pain and ulceration, people continue to wear shoes that do not fit the foot [8].

Given that, the individual variations in foot dimension are high, matching the shape of the foot to a suitable shoe style and therefore improving the fit can be challenging. In orthopaedic shoes the profile and depth of the toe box has previously been investigated for its association with increased plantar pressure under the toes [9,10]. Additional toe box depth did not however, improve skin lesion pathology in rheumatoid patients although pain and function scores did improve [10]. This type of orthopaedic shoe with greater toe depth is only worn by a small sample of the

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0958-2592/

population, often elderly, and little is known about the impact shoe styling and manufacturing variations have on the comfort of shoes worn everyday by younger generations.

A previous investigation demonstrated that the shoe of choice for everyday school wear is a flat ballet slip on pump [11]. This unstructured shoe does not provide any fastening or support and can easily fall from the foot on walking and has been previously characterised as a poor fit for patients who suffer from gout [12]. Recommendations for suitable fitting of footwear include (1) the presence of a fastening, (2) firm heel counter, (3) appropriate bending stiffness of the sole and (4) height of the heel [13,14]. According to published research reports, incorrect or poor fitting footwear can be detrimental to the wearer; for example an increase in heel height escalates forefoot plantar pressure [15], altered flare at the toe box being mis-matched to foot shape causing increases in toe pressure [16] and increased risk of falls in the elderly attributed to instability [17].

Footwear stability is most frequently researched within the areas of athletic and high-heeled shoes, with papers mainly focusing on medial and lateral foot stability and postural sway [18–20]. The way the sole is constructed and the sole material properties have been shown to influence stability and comfort in elderly populations with a thick-soled shoe reducing stability and a thinner firmer sole material being more preferable [21]. For heeled shoes though, increased instability is observed when there is a change of heel shape with narrowing of the heel impacting on the medial and lateral centre of pressure progression angle in the frontal plane [22]. Centre of Pressure (CoP) has been identified as the instantaneous point of application of the ground reaction force and the progression of CoP indicates the advances that this point makes during dynamic heel to toe walking [23]. Alterations in CoP progression from the longitudinal axis of the foot can be used to assess foot posture and motion during gait with a medial deviation being associated with a pronated foot type [24]. Motion of the foot whilst wearing shoes is known to provide challenges as the shoe inhibits motion capture [25]. CoP progression can be easily calculated from plantar pressure measurements and has been shown to identify deviations away from the midline of the foot and can be used as a measure of foot function identifying an altered pathway of motion [22,23].

To minimise discomfort and the potential for harm, it is important that a good fitting shoe is essential for everyday wear. The relationship of subjective comfort and the fit of a shoe clearly warrant investigation. Therefore, the primary aim of this paper is to examine the relationship between the perceived comfort whilst wearing three different flat ballet shoes which have an altered forefoot shape, volume and cantilever bending stiffness. Additionally, this study will investigate the impact of CoP progression during walking across these styles.

2. Method

2.1. Participants

Twenty-seven healthy females, from a convenience sample with an average age of 22.5 (±4.5) years, body mass of 63.3 (±8.9) kg, height of 1.64 (±6.5) m, UK shoe size 5.5 (±0.8), foot length 24.03 cm (±1.3) cm, foot girth – circumference of forefoot – 22.89 (±2.39) cm, and foot posture index 4 (±2), were recruited and provided full informed consent to participate in the study. Ethical approval was sought and granted from the university ethics committee. All subjects included in the study were asymptomatic at the time of testing and were excluded if any musculoskeletal foot and ankle pathologies were present. Foot sizing length and breadth measurements, for correct shoe size allocation, were taken

Fig. 1. Three footwear styles investigated: A4L = square shoe left size 4, B4L = pointed shoe left size 4, C4L = round shoe left size 4.

using a Brannock device® (The Brannock Device Company, NY, USA).

2.2. Footwear characteristics

The style of shoe chosen to investigate was a slip on flat ballet pump. The three toe box shapes were round, square and pointed. This shoe was selected as it has been highlighted as the everyday shoe of choice by young females [11]. All the shoes were black in colour, leather uppers and design on the toe box was matched with a feature of a bow or buckle styling (Fig. 1). The brand of each shoe varied between shoe conditions, with each shoe being purchased from a different retail outlet, and was blinded by covering the logo inside the shoe with micro lining top cover material (Algeos, Liverpool, UK). These features were controlled to minimise preference in brand and design that may influence comfort scores. The heel height on all shoes was standardised to 5 mm, weight of shoe was measured as Square = 192 g, Point = 164 g and Round = 145 g and the sole unit had a smooth tread pattern for each shoe style. The toe box shape and volume of the shoe upper varied between each style

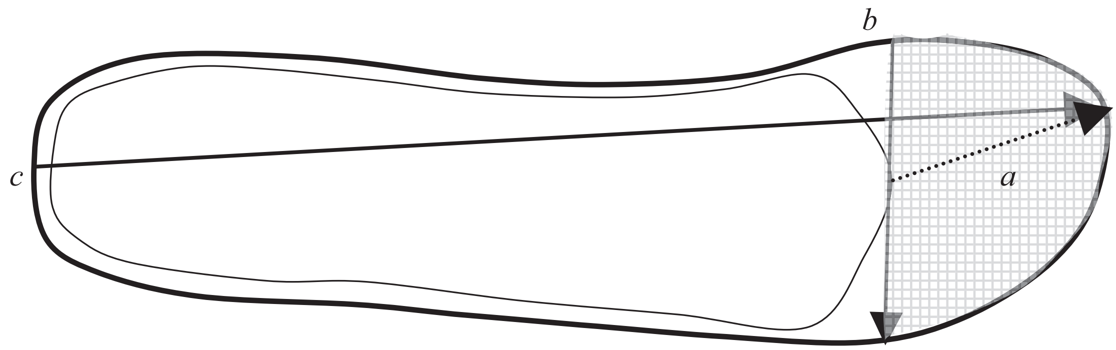

Fig. 2. Calculated shoe dimension characteristics: (a) *Volume* from end of shoe to end of vamp – shaded area indicating the volume of the toe box; (b) *breadth* of shoe measured at the widest horizontal point and (c) *length* of shoe measured from the midpoint of the heel to the end of the shoe in the longitudinal plane.

as well as the width and length of each shoe and the cantilever bending stiffness.

The volume of the toe box was measured by calculating the average quantity of a fine substance that filled the toe box to a defined point from the end of the shoe to the throat of the vamp of the shoe. The length of the shoe was defined as the longitudinal measure from the midpoint of the heel to the tip of the shoe and the width as the broadest part of the shoe in the horizontal plane. The averaged value reported for each shoe shape is a mean value for each shoe shape calculated from the four different sizes for each shoe shape used within the study (Fig. 2).

The cantilever bending stiffness was measured as described by Oleson et al. [26]. Four pairs of shoes (eight samples in total) were tested for each shoe style. The samples were individually clamped to a custom made rigid last and loaded on the plantar sole unit with a displacement rate of 2.5 mm/s (Fig. 3). The distance between the bending axis of the shoe and the loading axis of the load frame was equal to 40 mm. Each sample was subjected to two preconditioning load/unload cycles followed by a single loading cycle. No measurement was performed during preconditioning. During the last load cycle the displacement of the piston and the applied force were recorded at 100 Hz and utilised to calculate the value of bending angle and bending moment [26]. After the completion of the tests the initial stiffness (i.e. the initial slope of the moment/angle curve) as well as the work input (i.e. the area under the moment/angle curve) was calculated for each shoe sample (Fig. 3). Work input was calculated for bending angles between 0° and 20°.

2.3. Comfort

A 150 mm visual analogue scale was used to assess the comfort characteristics of each shoe [27]. Modifications to the original scale were made to specify different parts of the shoe that were to be assessed as comfortable on a scale of not comfortable at all to most comfortable imaginable. Statements to score on the scale included (1) overall shoe comfort, (2) heel cushioning, (3) ball of the foot cushioning, (4) side to side support, (5) arch height, (6) heel fit, (7) toe box, (8) ball of foot width and (9) length. Subjects were asked to score on the scale how they perceived the comfort of each of the three shoes tested after walking along a walkway of 10 m, turning and returning to the start point covering a total distance of 20 m. This was used as a representation of the distance travelled in a shoe shop when purchasing and trying on new shoes. The maximum comfort for each item was equal to a score of 150 and the minimum 0. The order of shoe allocation was given in a randomised order with each subject choosing a folded card identifying the order of the shoe and barefoot test condition.

2.4. Centre of pressure progression

The CoP progression angle was calculated from plantar pressure data that was collected whilst the subject walked the 20 m distance set for comfort assessment. This data were captured using a 1 m pressure plate (Footscan, RsScan Olen, Belgium). The plate was built into the walkway and placed 4 m along a total length of 10 m. This enabled the subjects to attain a normalised walking

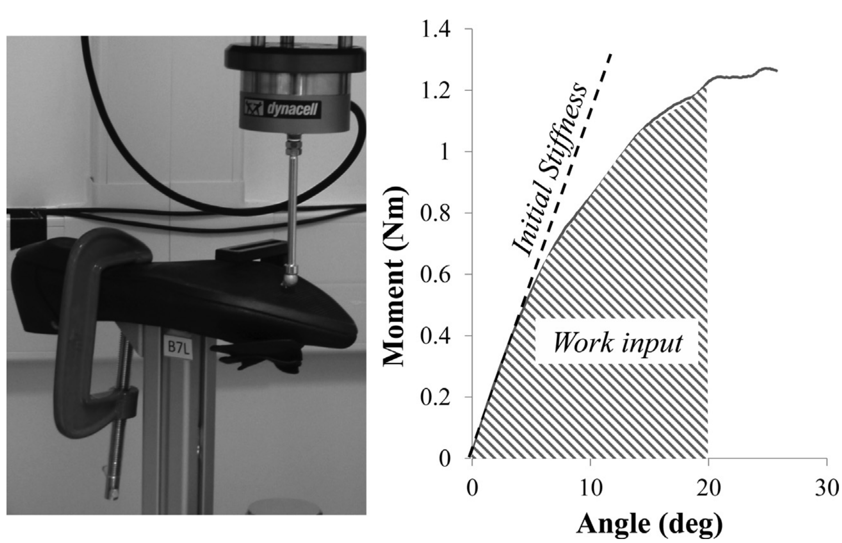

Fig. 3. The experimental set-up for cantilever bending tests (left) and a typical bending moment/angle curve (right).

Table 1
Shoe characteristics, measures of length, width, volume and bending stiffness with ±SD and significant *p* values ($p < 0.05$).

	Length (mm)	Width (mm)	Volume (mm^3)	Bending stiffness (N m/deg)	Work input (N m deg)
Square	250.75 ± 12.39†,*	80.75 ± 3.78†,*	58.75 ± 10.9	0.105 ± 0.006†,*	16.6 ± 1.4†,*
Round	252.5 ± 15.8‡,*	78 ± 3.91	46.25 ± 7.76‡,*	0.056 ± 0.021	10.7 ± 1.6
Point	258.5 ± 9.81†,‡	78.5 ± 3.11	58 ± 10.1	0.072 ± 0.010	12.5 ± 2.1
P value	0.0005	0.0005	0.005	0.0003	

Statistical significance between barefoot and shoe condition shown as *ANOVA $p = <0.05$ and where the difference lies indicated as follows.
† Significantly different to round.
‡ Significantly different to square.
§ Significantly different to point.

speed prior to data capture and prevent stepping onto the Plate [28]. The data collected were processed using computer programme written specifically for this study using Matlab (r2013a, Mathworks Inc., USA) to calculate the progression angle, contact time and velocity of the centre of pressure at the following times in gait [24]:

- Initial contact phase = ICP (heel strike 0% of stance phase).
- Forefoot contact phase = FFCP (forefoot loading 35% of stance phase).
- Foot flat phase = FFP (midstance 50% of stance phase).
- Forefoot push off phase = FFPOP (toe off 100% of stance phase).

The overall CoP progression angle calculated from the relative CoP displacement was defined as the deflection between the centre of pressure direction and the longitudinal axis of the foot [24].

2.5. Data analysis

Comfort for each of the nine individual parameters was scored out of 150 and a total comfort score was calculated for each shoe out of 1350, these scores were then averaged for all subjects. Statistical analysis to test if one shoe was more comfortable than another was completed on comfort scores using a Freidman test ($p \leq 0.05$) looking specifically at differences between conditions for overall comfort, width comfort, toe comfort and length of shoe comfort.

Changes of CoP progression angle from barefoot to wearing shoes were tested with a one way repeated measure ANOVA ($p \leq 0.05$) with post hoc Bonferroni testing. Correlations between comfort and shoe characteristics were evaluated using a Spearman-rho with calculated coefficient of determination and significance levels. Strength of relationships between variables were graded as small when $r = 0.10–0.29$, medium when $r = 0.30–0.49$ and large 0.5–1.0 [29].

3. Results

3.1. Footwear characteristics

The shoe characteristics measured showed significant differences between shoe style for length, width, toe box volume and cantilever bending stiffness (Table 1).

3.2. Comfort

Between the shoes tested, there was no significant difference in overall comfort ($p = 0.146$). Evaluation of the pointed shoe showed the highest mean overall comfort score at 643 with the round shoe being scored at 635 and square assessed as the least comfortable with an overall mean comfort score of 555, each shoe being scored out of 1350. The square shoe however, was most comfortable in the toe box area with a mean comfort score of 75 with the pointed shoe scoring 69 and round 65 out of 150, but there were no statistically significant differences in comfort when analysed with a Friedman test ($p = 0.495$). Comfort scores for length showed the square shoe to be least comfortable with 68 then point 73 and round 79 out of 150, yet again no significant differences were seen in these results ($p = 0.919$). Similarly, the width of the shoe comfort scores ranked the round shoe being least comfortable with a score of 65, point 69 and square 71 out of 150, these comfort scores were also not significantly different ($p = 0.368$).

3.3. Centre of pressure progression

Significant differences ($p \leq 0.05$) were seen in the CoP progression angle between the barefoot condition and all three shoe conditions with the barefoot condition angle being placed medial to the longitudinal axis of the foot (Table 3). The pointed shoe was significantly different to the barefoot and square condition at FFCP (forefoot loading) and the barefoot condition was significantly different to all shoe conditions at FFPOP (toe off) with the COP progression angle moving significantly more lateral to the longitudinal axis of the foot (Fig. 4).

Correlation between comfort and the measured variables (shoe length, width, volume, cantilever bending stiffness and centre of pressure progression angle) are provided in Table 2. There were no statistical significant correlations between comfort scores and shoe characteristics. However, small and medium strength relationships were observed.

Table 2
Spearman rank (rho) correlation coefficients for correlation between overall, width, toe box and length comfort scores and individual shoe characteristics. Negative values are showing a negative relationship, strength of relationship determined by position of rank small $r = 0.10–0.29$, medium $r = 0.30–0.49$ and large $r = 0.50–1.0$. Shaded value shows a medium strength relationship although statistical significance was not found.

Shoe type	Characteristic	Comfort			
		Overall	Width	Toe box	Length
Square	Length	−0.239	−0.244	−0.25	−0.067
	Width	−0.239	−0.244	−0.25	–
	Volume	−0.239	−0.244	−0.25	–
	Stiffness	−0.126	−0.176	−0.162	–
	Cop progress	−0.055	−0.155	0.75	−0.171
Round	Length	0.020	0.202	−0.010	0.069
	Width	0.020	0.202	−0.010	–
	Volume	0.020	0.202	−0.010	–
	Stiffness	0.357	0.182	0.117	–
	Cop progress	−0.18	0.038	−0.228	−0.190
Point	Length	−0.209	−0.051	−0.229	−0.238
	Width	−0.209	−0.051	−0.229	–
	Volume	−0.157	0.006	−0.146	–
	Stiffness	0.209	0.051	0.229	–
	Cop progress	−0.066	−0.176	−0.363	−0.275

Table 3
Centre of pressure progression for each of the contact phases for each shoe condition.

Measurements	Shoe style				
	Barefoot	Square	Round	Point	*p* value
Time % of COP progression					
ICP	10.18 ± 3.34	11.08 ± 2.25	10.48 ± 4.37	11.98 ± 3.31	0.137
FFCP	16.32 ± 9.78	17.98 ± 13.5	13.99 ± 9.4	14.28 ± 9.85	1
FFP	31.15 ± 12.26	29.31 ± 14.5	38.01 ± 13.15	33.33 ± 10.91	0.4
FFPOP	42.65 ± 8.23	41.34 ± 8.2	36.77 ± 8.7	40.02 ± 6.2	0.06*,†
Progression angle of COP					
ICP	3.88 ± 5.05	−9.67 ± 7.71	−9.96 ± 7.71	−15.28 ± 13.11	0.005*,†,‡,
FFCP	4.61 ± 3.27	4.29 ± 2.81	5.30 ± 2.98	7.07 ± 2.77	0.004*,
FFP	1.52 ± 3.27	0.31 ± 4.8	−0.25 ± 2.88	0.99 ± 2.85	0.147
FFPOP	−13.77 ± 8.5	−2.10 ± 4.78	−0.60 ± 4.82	−2.51 ± 3.9	0.005*,†,‡,
Velocity of COP (cm/s)					
ICP	0.45 ± 0.14	0.39 ± 0.11	0.43 ± 0.13	0.34 ± 0.12	0.02*,
FFCP	0.53 ± 0.32	0.65 ± 0.4	0.63 ± 0.2	0.7 ± 0.4	0.12
FFP	0.43 ± 0.18	0.43 ± 0.15	0.4 ± 0.1	0.37 ± 0.1	0.1
FFPOP	0.29 ± 0.04	0.32 ± 0.05	0.29 ± 0.07	0.32 ± 0.06	0.26
Overall Progression angle					
Progression angle	−2.53 ± 3.46	−0.59 ± 2.09	−0.01 ± 1.91	0.09 ± 1.62	0.01*,†,‡,

Statistical significance between barefoot and shoe condition shown as
* ANOVA $p = <0.05$ and where the difference lies indicated as follows.
† Barefoot significantly different to round.
‡ Barefoot significantly different to square.
§ Barefoot significantly different to point.

4. Discussion

4.1. Footwear characteristics

The most significant measured difference between the shoes was the longitudinal length measured, with each shoe of the same marketed size being significantly different in length to the other. The increased length was mainly due to the alterations in styling at the toe box and was therefore, not a true representation of how the foot sat within the shoe. Although each subject's foot length was matched to the correct shoe size, the impact that the shoe last design and fit had on the individual's foot were not accounted for. This disparity between shoe fit, shoe length and last construction represents an authentic experience for the consumer faced with

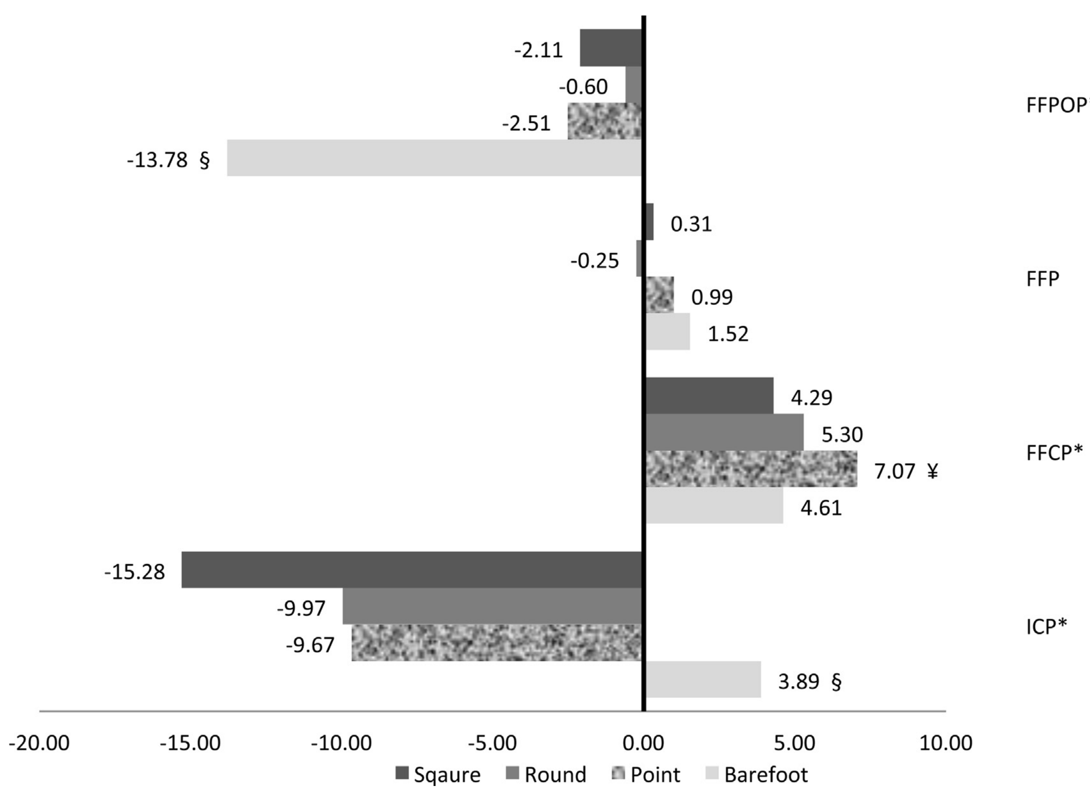

Fig. 4. Centre of pressure progression angle for the four phases of gait (ICP, initial contact phase; FFCP, forefoot contact phase; FFP, foot flat phase and FFPOP, forefoot push off phase). A negative value denotes the lateral side from the longitudinal axis of the foot (*significance $p = <0.05$, barefoot significantly different to all shoe conditions, [¥]point significantly different to square and barefoot).

irregular sizing and fit within the shops. Shoe sizing changes have been previously reported within running shoes where the marketed size is not representative of the actual size of the shoe [30]. If consumers are not aware of this sizing error, shoes that are too small or big could be worn without any knowledge by the user contributing to potential pathology [7].

Results from this study clearly indicate the mismatch between the fit and the advertised size of the shoe which has a huge potential to inflict both short and long term foot conditions/pathologies in individuals whom otherwise might not encounter these issues. In this context, the designers and the manufacturers of footwear should pay more attention to improve their product range and clinicians should increase the awareness of sizing issues between styles and manufacturers amongst the population with the choice of footwear.

When evaluating the cantilever bending stiffness of the sole unit of the shoes tested the square shoe was significantly stiffer than the round and pointed shoes. The stiffness of a sole unit is thought to influence foot function giving additional support and is often used in clinical interventions for hallux limitus [31]. However, the square shoe tested, which had the stiffer sole unit, demonstrated a small negative relationship with comfort. Similarly, the least stiff shoe tested was the round toe which had a medium strength positive correlation with comfort indicating that a stiffer soled shoe was least comfortable. All subjects included in this study were assessed as having no musculoskeletal pathologies. The subjects studied were not ailed by any restrictions in joint movement or did not express pain in the metatarsal joints therefore, when this observed normal range of toe flexion occurs a flexible soled shoe is more comfortable. This has been alluded to previously when the shoe has been shown to work with the flexibility and range of motion available in the metatarsophalangeal joints at toe off [26] and when a reduced amount of motion is observed, as in hallux limitus, using a stiffer sole shoe facilitates a relationship between shoe and foot reducing pain associated with pathology. Assessment and advice regarding footwear choice should reflect the individual's metatarsal range of motion when discussing the stiffness of the sole unit.

4.2. Comfort

Overall comfort score of the three shoes tested were not significantly different from each other despite the clear differences seen between the physical properties of the shoes. However, the mean overall comfort score for each shoe style failed to reach half way on the scale possibly demonstrating that all three shoes were not necessarily perceived by participants as a comfortable fit.

The ballet pump shoe has recently been downgraded as a desirable "fashion" item to an "essential" clothing item that every female must have, similar to hosiery. Although not through scientific evidence, the shoe is reported to be so popular due to comfort and ease of use that it is now referenced to as a clothing staple [32]. Although the test shoes in this paper were all classed as ballet pumps, they did have different shapes and physical characteristics. To avoid any confounding issues, the test shoes were not compared to the subjects own choice of shoe, neither was the use and individual preference of the ballet pump shoe. Further exploration into whether the test shoes used would have been chosen by subjects as the shoe of choice would help in analysis and discussion of results obtained.

As the chosen test shoes varied in toe box shape and volume, the comfort at the forefoot was investigated specifically to test the notion that a larger volume and broader toe box width would be more comfortable. There was, however no significant correlation between toe box width and volume and the comfort perceived in the toe box area. Although, the round shoe tested did demonstrate a small effect on size yet it was not statistically significant. This small effect could be attributed to the sample size and also variations in the sizing of the shoe. Yet interestingly, the round toe box shoe measured the smallest volume and narrowest width indicating that a smaller volume and width is perceived as more comfortable. Improved contact and sensory feedback from a snugger fitting shoe has been previously attributed to the wearer feeling more comfortable [5] as well as the material used to construct the upper [1]. All the tests shoes were made from leather but the stiffness and softness of the leather was not controlled. The flexibility and suppleness of the round shoe compared to the pointed and square shoe could have improved the comfort perception despite the reduced shoe dimension which may have improved sensory feedback. Footwear upper construction and material properties could therefore play a role in comfort perception of shoes as should be assessed when giving patients footwear advice.

A loose fitting shoe has been reported to alter walking velocity and stride length as the foot alters function in an attempt to keep the shoe on the foot [33]. The lack of fastening from the slip on ballet pump style shoe puts greater emphasis on the shoe needing to be a tighter fit to ensure that the shoe does not fall from the foot whilst walking. The round shoe condition being deemed the tightest shoe in fit with the smallest volume and width did cause a decrease in the duration of the stance phase. The square shoe being the widest and the one with a larger volume resulted in an increase in the duration of the stance phase. This supports the notion that a tight shoe results in a faster and a more efficient gait. Therefore with this style of shoe, subjects were more comfortable and produced a more efficient gait when wearing the smallest width and volume of shoe contradicting advice for footwear fit where emphasis is placed on room in the toe box [34]. The results from this study could help understand why people with foot pathology continue to prefer an ill-fitting shoe [6,8] even though the tightness and fit of the shoe may be contributory factor to foot pain and pathology. Developing further research and footwear design work to provide comfortable fashion shoes that do not contribute to foot pain and pathology would improve foot health particularly in females.

4.3. Centre of pressure progression

The influence of a shoe on the CoP progression angle was significant at all the identified events within the stance phase. At ICP (heel strike), there was a dramatic difference between the barefoot and the shoe conditions with all shoes causing an inverted heel strike. However, the participants exhibited a slight eversion during barefoot heel strike. The shoe conditions represent the observations made for normal walking [35] whilst barefoot condition fits to the reported normals seen by young subjects [24]. It is not clear from this study what impact this change has on gait but wearing a flat ballet shoe transforms barefoot walking.

At FFCP (forefoot loading), the pointed shoe was significantly different to the barefoot and square condition, which presented with similar medial deviated angles. It is unclear if any of the measured characteristics can help to discuss these results as the pointed shoe was assessed as being in the middle of the range for the different physical parameters tested. Whilst heel height and sole material were standardised, the contours of the pointed shoe were narrower than the other shoes mimicking the style of a high heel shoe. High heel shoes have previously been shown to alter medial and lateral centre of pressure progression in the frontal plane [22]. The styling of the pointed shoe heel may have resulted in an increased medial shift of the centre of pressure during midstance.

The barefoot condition at FFPOP (toe off) was the most lateral deviated from the longitudinal axis and was significantly different to all shoe conditions. At toe off the impact of wearing this style of shoe brings the CoP progression angle towards the midline of the foot and centralises the body over the foot providing a smoother more efficient locomotion. Further investigations as to whether CoP progression angle reacts this way in all shoe styles would help in the continued investigations and understanding of the effects wearing shoes have on gait, physical wellbeing and pathology.

5. Conclusion

The correlation between comfort and all physical characteristics were not statistically significant and only showed medium strength relationships highlighting that the length, width, toe box volume and cantilever bending stiffness of a shoe are not significantly related to the perceived comfort. However, the results indicate that in a popular ballet pump shoe, a snugger fit and more flexible sole unit is perceived to be more comfortable than a stiffer and wider shoe, and produces a more efficient gait, which may contribute to the continued popularity of this shoe choice despite the potential for foot pain and pathology.

Conflict of interest statement

All authors involved in this research and manuscript preparation have no conflicts of interest that would influence the work or impact the reported results.

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Appendix 15

STAFFORDSHIRE UNIVERSITY

Faculty of Health/Faculty of Sciences

ETHICAL APPROVAL FEEDBACK

Student name:	**Helen Branthwaite**
Title of Study:	**Footwear choice amongst teenage girls: a survey**
Status of approval:	**Approved**

Action now needed:

Your project proposal has now been approved by the Faculty's Ethics Panel and you may now commence the implementation phase of your study. You do not need to approach the Local Research Ethics Committee. You should note that any divergence from the approved procedures and research method will invalidate any insurance and liability cover from the University. You should, therefore, notify the Panel of any significant divergence from this approved proposal.

You should arrange to meet with your supervisor for support during the process of completing your study and writing your dissertation.

Comments for your consideration:

Thank you for forwarding the amendments requested by the Panel

Signed: David Clark-Carter
Chair of the Faculty of Health/Faculty of Sciences
Ethics Panel

Date: 1st February 2010

STAFFORDSHIRE UNIVERSITY
Faculty of Health

ETHICAL APPROVAL FEEDBACK

Name:	**Helen Branthwaite**
Title of Study:	**The effects of toe box shape in a shoe on comfort and forefoot pressure**
Status of approval:	**Approved**

Action now needed:

Your project proposal has now been approved by the Faculty's Ethics Panel and you may now commence the implementation phase of your study. If appropriate, you should now approach the Local Research Ethics Committee.

Comments for your consideration:

Thank you for forwarding the amendments requested by the Ethics Panel.

Signed: David Clark-Carter
Chair of the Faculty of Health/Faculty of Sciences Ethics Panel

Date: 10th June 2010

Appendix 16

The work presented, where Helen Branthwaite is the primary author have been designed, implemented, and written by Helen Branthwaite. Nachiappan Chockalingam acted as an advisor throughout and reviewed the manuscripts and contributed to some structural changes.

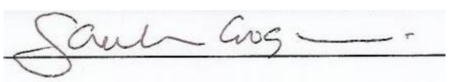
Sarah Johnson and Nina Davies are the primary authors in the respective papers on toe props and children’s shoes. These papers were completed under the supervision of Helen Branthwaite, who made a contribution to the conceptualisation of the idea, supervised and then subsequently prepared and published the manuscript.

Roozbeh Naemi, Marc Jones, Aoife Healy, Anand Pandyan, Sarah Johnson, Panagiotis Chatzistergos, Sarah Grogan and Andrew Greenhalgh have all played a part in data processing and analysis and have all reviewed the manuscripts.

Co Authors Supporting Statements

Sarah Grogan

I can confirm that Helen Branthwaite designed, ran, analysed and wrote up the paper Branthwaite, H.R., Chockalingam, N, Jones M, Grogan S. (2012) Footwear choices made by young women and their potential impact on foot health. Journal of Health Psychology 27(11): 1-10. I contributed some advice on analysis.



Panos Chatzistergos

I confirm my collaboration with Mrs Helen Branthwaite for the preparation of the manuscript entitled: *“The impact of different footwear characteristics on centre of pressure progression and perceived comfort.”* The aforementioned manuscript was submitted and accepted for publication in “The Foot” journal (currently in-press).

Mrs Helen Branthwaite led the design and the realization of this study as well as the preparation of the aforementioned manuscript.

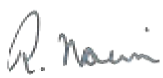
Aoife Healy

Branthwaite HR, Chockalingam N, Healy A. (2012) Footwear - the forgotten treatment - Clinical role of footwear. Goonetilleke, R.S. ***The Science of Footwear*** Chapter 16: 341-352. CRC Press.
I hereby certify that Helen Branthwaite made substantial contributions to researching the literature, writing and drafting the final approval of the chapter published.

Roozbeh Naemi

Johnson, S., Branthwaite, H.R., Naemi R., Chockailngam, N. (2012). **The effect of three different toe props on plantar pressure and patient comfort** *Journal of Foot and Ankle Research*, 5:22 doi:10.1186/1757-1146-5-22.
http://www.jfootankleres.com/content/5/1/22

I confirm that Helen Branthwaite made substantial contributions to this manuscript and I was involved in data processing.



Sarah Johnson

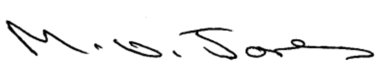
Johnson, S., Branthwaite, H.R., Naemi R., Chockailngam, N. (2012). **The effect of three different toe props on plantar pressure and patient comfort** *Journal of Foot and Ankle Research*, 5:22 doi:10.1186/1757-1146-5-22.
http://www.jfootankleres.com/content/5/1/22

I confirm that Helen Branthwaite made substantial contributions to this manuscript and I was involved in research design, data acquisition and data processing

Marc Jones

Branthwaite, H.R., Chockalingam, N, Jones M, Grogan S. (2012) **Footwear choices made by young women and their potential impact on foot health.** *Journal of Health Psychology* 27(11): 1-10.

Helen was the lead researcher on this study co-ordinating the project and leading on the research design, data collection, data analysis and write up.



Andrew Greenhalgh

I confirm that Helen Branthwaite was the lead researcher for the work "**The effect of shoe toe box shape on forefoot interdigital and plantar pressures.** *Journal of Foot and Ankle Research*. 6:28 doi: 10.1186/1757-1146-6-28." I was involved in data processing and revision of manuscript prior to publication.

Anand Pandyan

I confirm my collaboration with Mrs Helen Branthwaite on the following 2 manuscripts where she led the design and anlaysis plan as well as the preparation of manuscripts for publication.

Branthwaite, H.R., Chockalingam, N., Pandyan, A., Khatri, G., (2012) **Evaluation of lower limb electromyographic activity when using unstable shoes for the first time: A pilot quasi control trial.** *Prosthetics and Orthotic International*. 37(4): 275-281.

Branthwaite, H.R., Pandyan, A., Chockailngam, N. (2012) **Function of the triceps surae muscle group in low and high arched feet: An exploratory study.** *The Foot* 22(2): 56-59.