The Effects of Heel Height, Shoe Volume and Upper Stiffness on Shoe Comfort and Plantar Pressure

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Declaration

I declare that this thesis and the work contained are my own work and are the results of my own course of research, whilst studying at the University of Salford from July 2010 until October 2014. I confirm that all sources and materials have been acknowledged.

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Abbreviations

A - Line on the body weight vector

BS – British Standard

C_1 – Distal cone point

C_2 – Proximal cone point

EMG - Electromyography

F – Force under the forefoot

f – Moment arm of F

H – Force under the heel

H_0 – Heel point

h – Moment arm of H

M1 – Medial forefoot angle

M2 – Lateral forefoot angle

MPJ1 - Metatarsal phalangeal joint one

MTJ5 - Metatarsal phalangeal joint five

MTP2 - Metatarsal phalangeal joint two

MTP3 - Metatarsal phalangeal joint three

MTP4 - Metatarsal phalangeal joint four

MT24 - Metatarsal phalangeal joint two – four

RB – Reckitt Benckiser

T_0 – Toe point

VAS – visual analogue scale

Abstract

The research in this thesis investigated the independent effects of changing heel height, forefoot shoe volume and upper material stiffness on plantar pressures and comfort in ladies raised heel shoes. Plantar pressure is widely associated with comfort and foot pain including conditions such as subchondral bone microfractures, cartilage degeneration, osteoarthritis, hallux valgus, plantar calluses, metatarsalgia, morton's neuroma, and hammer toe. Reducing peak plantar pressure at localised foot regions is therefore an aspiration of footwear manufacturers and health professionals alike.

As a precursor to the primary investigations, protocols for measuring plantar pressure were investigated. Specifically, how long it takes for a participant to acclimatise to new footwear and how many steps must be measured to provide valid plantar pressure data are research design issues not thoroughly resolved by prior research. In the first study within this thesis it was found that 166 steps per foot were required to acclimatise to unfamiliar footwear. Also, that data from 30 steps should be collected to ensure sufficient data for a representative step could be accurately calculated (within error of +/-2.5%) assumed

The second study investigated the effects of incremental increases in heel height and upper material stiffness on comfort and plantar pressure. It was found that an increase in heel height of 20mm was required for a significant 19% increase in plantar pressure at MTP1 in shoes which have a heel height under 55mm. A significant increase in pressure was observed with just a 10mm increase in heel height for shoes over 55mm.

Similar, though smaller, effects were observed for perceived comfort in different heel heights.

The third study investigated the effects of shoe volume and upper stiffness on comfort and plantar pressure. It was found that an increase in shoe volume increased the pressure at the MTP1 and reduced it at the heel. There was also a volume, the medium volume shoe, which clearly produced the significantly lowest pressure at the MT24 (275kPa medium shoe compared to 289kPa and 305 kPa in the smallest and largest volumes respectively). A significant interaction between shoe volume and material stiffness was also observed: when the material stiffness is changed the amplitude of the effect due to volume is magnified.

Of the three footwear features investigated heel height has the greatest significant effect on both comfort (74% increase in overall discomfort for 35mm to 75mm heel height) and plantar pressure (33% increase at MTP1 between 35 and 75 mm heel height), followed by shoe volume then upper stiffness. There was a clear relationship between plantar pressure and comfort and the results suggest that shoes with an effective heel height over 55mm should be considered different from those with heel height less than 55mm. This serves to define a “high heeled“shoe.

To ensure that set measurements could be defined investigations into the effects of heel height were completed with only one shoe size. Thus for other shoe sizes scaling may be required. The results of this thesis will improve the quality of future investigations because it has provided guidelines on the required number of steps to acclimatise to unfamiliar footwear, and the number of steps required to produce an average representative step. Also, to the benefit of researchers, the results of this thesis have highlighted the difficulty in controlling features of footwear such as the stiffness of the upper material whilst simultaneously demonstrating the importance of controlling this feature. For both shoe manufactures and research these results have shown the effect of a systematic increase in heel height which has enabled the first pressure and comfort based definition of a high heeled shoe. From this information designers will have a greater understanding of how their designs will have an effect on the plantar pressure and comfort experienced by the wearer.

Chapter 1: Introduction to Thesis

Chapter 1: Introduction to Thesis

The annual value of shipments of female non athletic shoes in the United States of America was $263 million in 2002 [1]. It has also been shown that 37% of women wear high-heeled shoes for work [2]. From these two findings it is reasonable to deduce that at least $97.31 million are spent on high heels in the U.S annually.

Females are the predominate wearers of high heels, and the gender that have the highest rate of lower limb health problems, a link that some believe is not coincidental [3]. Past research has shown that there are many gait, health and comfort problems related to ill-fitting shoes [4-8] and high heeled shoes are frequently implicated as the cause of common but painful and disabling conditions [9-11]. Women that are regular wearers of high heels i.e. they wear high heels at least 3 times a week [12, 13], can expect: shortened gastrocnemius medialis fascicle length [5], increased Achilles's tendon stiffness, reduced ankle active range of motion [6], increased risk of lateral ankle sprain [7], reduced medial gastrocnemius muscle efficiency [8], increased shock wave from heel strike and 'metatarsal strike' [14], subchondral bone microfractures (which would lead to articular cartilage degeneration and osteoarthritis) [15] and increased risk of Hallux valgus and plantar calluses [5]. All of these conditions are a result of the altered distribution of plantar pressures or the restricted movement of joints that are the result of with walking in high heeled footwear.

It has been demonstrated that when the high pressures produced by wearing high heels are applied to a forefoot that is affected by diabetes there is an increased risk of ulceration [16]. Even in the absence of disease, forefoot pain has been reported as synonymous with increased plantar pressure [17, 18]. Thus, high heeled footwear has been strongly associated with poor foot health [9-11, 19]. A detailed review of the literature related to health problems associated with use of high heeled footwear is presented in chapter 2.

Despite the apparent risks of wearing high heeled shoes, most people still consider aesthetic design as their primary concern when choosing footwear [20, 21]. Subsequently, it is clear that to improve both shoe comfort and foot health we need to understand how choices made in the design of aesthetically pleasing footwear affect the foot and lower limb. If the relationships between design features of heeled footwear, plantar pressure, and comfort were better understood, then some aspects of heeled footwear design could be adjusted to try and achieve a better balance between aesthetic requirements and foot health. Such improvements in current understanding would lead to the development of more comfortable, healthy, yet fashionable and aesthetically pleasing heeled footwear. This aspiration was a key motivating factor for the work in this thesis.

High heeled shoes are a popular category of shoe and as a result many footwear studies have investigated the effects of heel height on plantar pressure and other aspects of gait (covered in detail in chapter 2). However, most research has directly compared shoes with multiple contrasting design features and shoes of varied type, such as high heels and sneakers [11]. Since heel height was not controlled as an independent variable in previous studies we remain unable to quantify the precise effect of heel height on specific aspects of gait, such as plantar pressure, nor comfort. Previous studies have also measured changes in pressure under the foot and comfort assuming they are related [17]. However, just as plantar pressure is likely to be affected by multiple aspects of footwear design, so too comfort is multifactorial. Furthermore, it is a subjective rather than objective quality and thus not likely directly correlated to plantar pressure but due to the influence of other factors too. Thus, whilst studies to date have improved current understanding of the likely gross effects of heel height on plantar pressure and perhaps comfort, the data is not suitable for implementation in any footwear design process.

Elevating the height of a shoe heel will necessarily impose other changes in footwear design choices since few (if any) footwear design features are not coupled to others. For example, as heel height is increased the upper design including the upper volume and material stiffness will be adjusted. Shoe volume maybe reduced and upper stiffness increased in heeled footwear to compensate for the change in foot position, foot behaviour when the heel is elevated, and to meet aesthetic requirements. However, the literature is not clear on the independent effects of design features such as forefoot volume and upper material on comfort and forefoot plantar pressure. If, as is assumed, high heels lead to elevated forefoot plantar pressures, changes in upper volume or stiffness may usefully counteract the effect of the heel height, without significant compromise on aesthetics. However, due to a lack of systematic investigation of these two design features, and how they are coupled with the effects of changes in heel height, improving the design of heeled shoes is currently not foot health orientated or systematic.

The research in this thesis therefore focussed on addressing important gaps in the literature concerned with the design of high heeled shoes for women. The research investigates the independent effects of changing heel height, forefoot shoe volume and shoe upper material properties on forefoot plantar pressures and comfort.

To investigate the effect of footwear features such as heel height and upper properties on plantar pressure, a suitable measurement protocol is required. Instruments to measure plantar pressure inside shoes are well established and past research has shown that between successive measurements several days apart the variation in peak plantar pressure data can be just 3% [22]. However, different footwear designs, especially those to which a research participant is unaccustomed, may represent a large perturbation in the conditions of walking. Consequently a participant may need to acclimatise to different footwear designs. This issue is widely acknowledged in the protocols employed by researchers in the literature [17, 23-25], but acclimatisation practices vary a great deal.

It has been shown that just 12 steps are required to produce valid and reliable data of gait for people with diabetes wearing custom made diabetic rocker shoes [26]. However, heeled footwear represents a different perturbation and it is not known how high heeled footwear and changes to upper features (i.e. forefoot shoe volume and stiffness) affect gait. Consequently, there are no clear guidelines on the number of steps required to produce valid and reliable data in unfamiliar footwear. Furthermore, before valid data is collected there is likely to be a period of acclimatisation to the unfamiliar footwear. This acclimatisation period is likely to be sensitive to the shoe design, and therefore the number of steps that are required to provide a true measure of the footwear effect on plantar pressure might vary between footwear designs. This issue has not previously been investigated.

As a result of these findings, a further aim of this thesis was to investigate how long research participants required to become acclimatised to variations in footwear design and also how many steps must be measured thereafter to measure the effect of the shoe on plantar pressure.

In summary, the overarching goal of this research is to improve current understanding of the dependence of forefoot plantar pressure and comfort in high heeled shoes on heel height, shoe volume, and upper material stiffness, in order to improve shoe comfort and foot health. This will be achieved through a background information search and detailed literature review (chapter 2), and three subsequent experimental studies:

- Investigation of research protocols and the number of steps required for acclimatisation to a new shoe, and the number of steps required to obtain valid plantar pressure data (Chapter 3).
- Investigation of the effects of heel height and upper material stiffness on plantar pressure and comfort (chapter 4).

- Investigation of the effects of shoe volume and material stiffness on plantar pressure and comfort (chapter 5).

Figure 1 provides an overview of the key topics areas in this thesis and how they interlink.

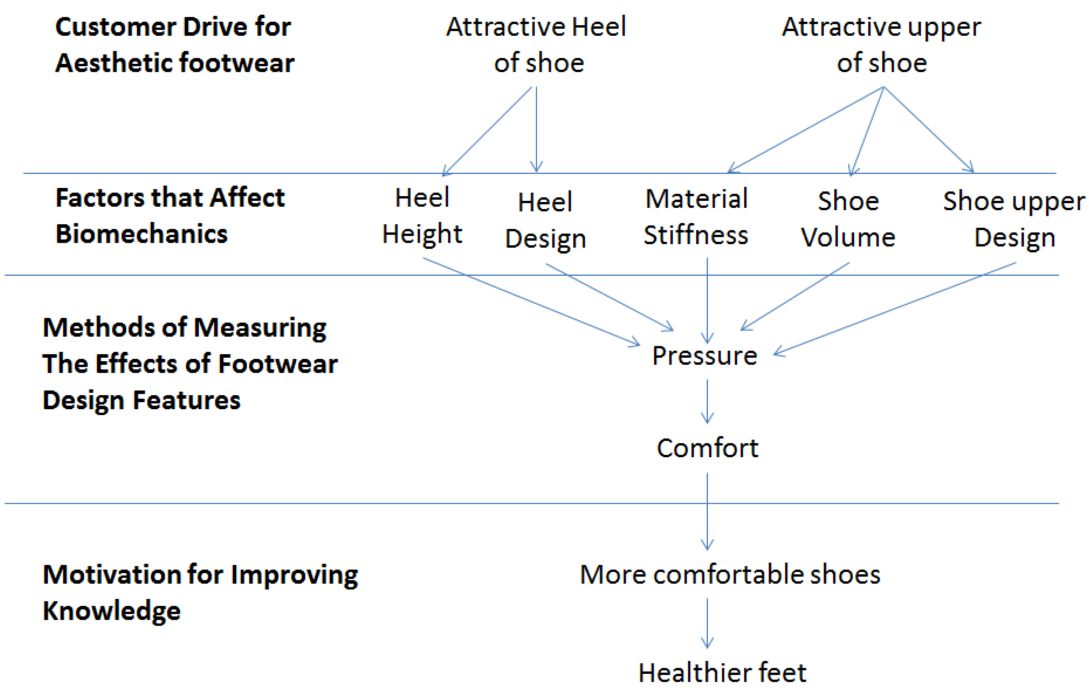

Figure 1: A Flow diagram represent to key areas of study for this PhD thesis

Chapter 2: Background and Literature review: High heeled shoes

Chapter 2 Introductory outline:

The aim of this chapter is to present background information and a literature review relevant to the focus of this thesis. In the first section, definitions of the high heeled shoe and heel height are explored. In the second section, the anatomy of footwear lasts and footwear are considered, focusing on those features most relevant to high heeled footwear which affect foot biomechanics and foot health.

In the third section, the effects of habitual high heeled shoe use, including the effects on the trunk, hips, knee, ankle and foot biomechanics are considered. A review of effects of high heeled shoe features on plantar pressure and how footwear features might relate to pathology is also presented. In the final section, potential improvements in high heeled footwear design are considered as a basis for the subsequent studies. A reflection on prior research designs and protocols is also presented.

2.1. High Heeled Shoes:

A high heeled shoe is a type of footwear which forces the proximal foot (heel) to be significantly higher than the distal foot (forefoot) during stance. This is achieved via adding a tall piece of solid material beneath the heel of the foot, whilst typically maintaining a relatively thin material below the forefoot. Though there are many variations in both heel and upper design, most high heels are made up of the same common parts, as shown in Figure 2.

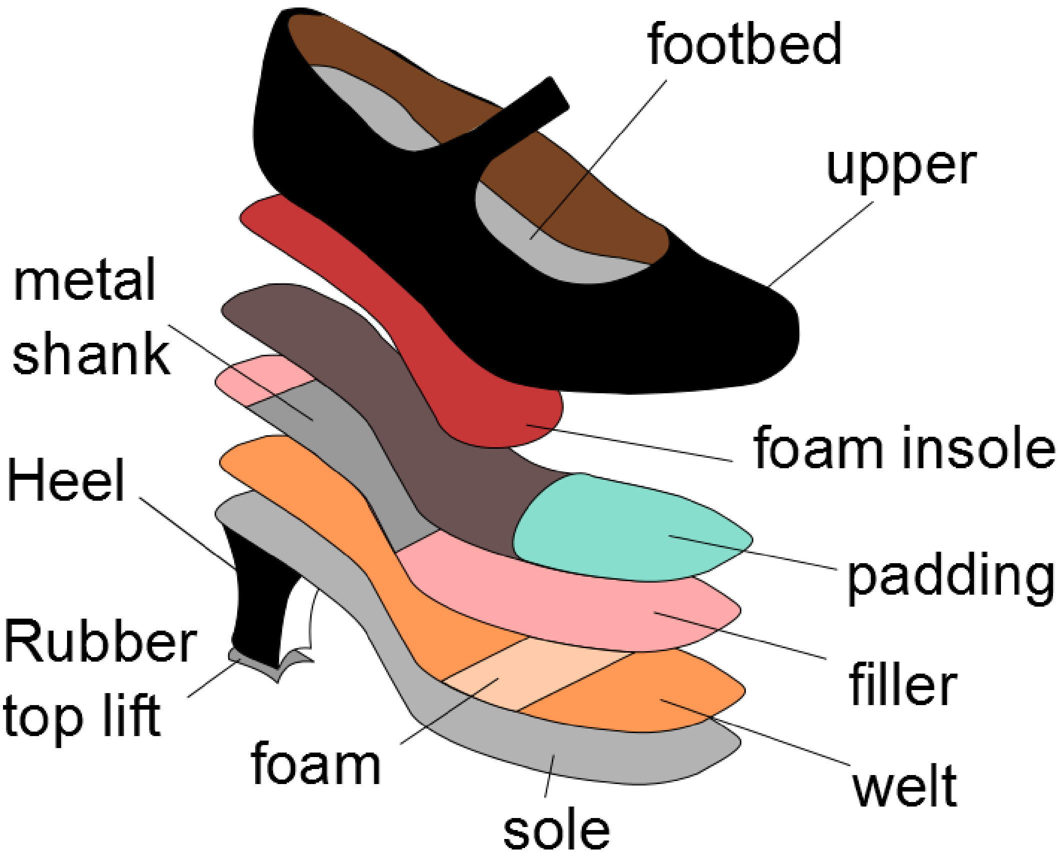

Figure 2: The structure of a high heeled shoe

The many parts which make up a high heel can each dramatically affect the performance of the shoe including its comfort [27] and the pressure distribution [28] experienced on the plantar surface, and therefore the way in which we should describe the shoe. Past research has shown that increasing heel height changes the mechanical behaviour of the foot, including its dimensions (such as length), movement, and its damping characteristics (by making the foot stiffer which inhibits its ability to dissipate loading across the plantar surface) [29, 30]. Due to the effects of raising the heel height it is logical to classify the height of the heel as "high" or "low" by its expected influence on the foot. For example, assuming dorsiflexion of the first toe engages the windlass mechanism model [31], a shoe might be classed as 'high heeled', when it increases first toe dorsiflexion and thereby increases the engagement of the windlass mechanism (i.e. increases tension in the plantar fascia). The windlass mechanism is thought to become engaged when the toes are extended 10° [31]. For an average ball length of the female foot (177.6 cm [32]) we can assume that the windlass mechanism is engaged when the difference between the height of the base of the heel and forefoot is 7cm (which would extend the toe by 10°). This is slightly higher than the general perception in the literature that defines high heeled shoes investigated as having a heel over 6 cm, as discussed later in this section and shown in Table 1. Regardless, this serves as an example of how a functional effect of a high heeled shoe (engagement of the windlass mechanism) could be used to define the shoe as "high".

Investigators have tested a large range of heel heights within what are thought to be "high heeled shoes". The lowest heel that has been called a "high heel" was only 3 cm [33, 34], whilst the largest heel found in the literature was 11 cm [8]. whilst there are these extreme cases researchers tend to define heel heights between 6 and 8 cm as high, although there are several studies that cluster around a heel height of 9-9.53 cm. Table 1 provides a detailed breakdown of the definition of "high heeled" shoes previously investigated in 43 studies, and a list of the primary reported effects is given, which describes the evidence found showing that the heel height investigated was sufficient to influence the foot and gait (Table 1).

Very few researchers provide a reason for their definition of heel height as “high”. Some studies copy past research and then test a heel they deem to be of similar height [35]. Others rely on recommendations of last makers [36]. Lee et al [37] found that women were most “inconvenienced” by heels that were 6-9 cm and used this as a basis for their future work. The definition of 6 cm and over is in agreement with the only established text book found to clearly define a high heel: equal to or above 6 cm, with a low heel equal to or below 2 cm [38]. Unfortunately the book does not provide any reason for this proposed rule. Further discussions with the author revealed that this value was used because it was the most consistent in the literature. However, there was no distinct biomechanical, comfort or other factor underlying their reasoning. Due to 6cm being both one of the most reported definitions for a high heel, for the purpose of consistency with prior work it will be the initial definition of a “high heel” for the remainder of this thesis (with the potential to review this as a result of the investigations undertaken).

Table 1: An overview of high heel papers and their outcome

Paper	Heel heights used	Definition of a high heel	Effect of walking high heeled shoes
The effects of increasing heel height on forefoot peak pressure. Mandato and Nester 1999 [39]	Sneaker, shoes with 2-inch and 3-inch heels.	Both heeled shoes considered high therefore a high heel is at least 2-inches (5cm), however there wasn't any information on the sole thickness below the forefoot.	Increased heel height increases pressure at the first metatarsal head and hallux, with an overall increase in pressure under the forefoot.
Influence of heel height and shoe insert on comfort perception and biomechanical performance of young female adults during walking. Hong et al 2005 [25]	Flat (1 cm), low (define as 3.8 cm in abstract but 5.1 in main text), and high (7.6 cm)	7.6 cm and over is considered high, no clear reason given for this definition and no information on forefoot sole thickness.	In high heels the plantar pressure in the heel and midfoot moved to the medial forefoot, and the vertical and anteroposterior ground reaction force increased.
Effects of shoe characteristics on dynamic stability when walking on even and uneven surfaces in young and older people. Menant et al 2008 [40]	A standard oxford shoe with a 27mm heel and 13 mm under the forefoot, plus a shoe with 4.5mm elevation added to the original 27mm heel with a 13mm sole under the forefoot. These were chosen because they report a past study that showed wearing heels of greater than 2.5cm almost doubles the risk of falling. [41]	No shoe was defined as a high heel.	Both young and old subjects used a conservative walking pattern in the elevated heel shoes.
Effects of shoe inserts	Flat (1 cm), low (5.1 cm),	7.6 cm considered high but no	Increased heel height increases impact force, medial

and heel height on foot pressure, impact force, and perceived comfort during walking. Lee and Hong 2005 [42]	and high (7.6 cm).	clear reason given to why. There is no detail on the thickness of the sole below the forefoot.	forefoot pressure, and perceived discomfort.
Lower extremity mechanics and energy cost of walking in high-heeled shoes. Ebbeling et al1994 [27]	1.25cm, 3.81 cm, 5.08 cm, and 7.62 cm chosen to reflect the range of heel heights from “flat” to “spike”	No shoe was clearly defined as a high heel nor was there detail provided on the thickness of the sole below the forefoot but all shoes are said to be of similar construction.	Ankle plantar flexion, knee flexion, vertical ground reaction force, and the maximum anteroposterior breaking force increased with increased heel height, as well as heart rate and oxygen consumption. There were much larger differences between the 7.62 cm heel and the 5.08 cm heel compared to the difference between the 5.08cm and the 3.81 cm heels. These include the ankle touchdown angle (-28.2 for 7.62cm, -17.9 for 5.08cm, and -12.9 for 3.81 cm heel), the ankle maximum plantar flexion (-34.5 for 7.62 cm, -25.6 for 5.08cm, and -21.5 for the 3.81 cm heel).
High heeled shoes: their effect on centre of mass position, posture, three-dimensional kinematics, rearfoot motion, and ground reaction forces. Snow, keith, and Williams 1994 [43]	1.91, 3.81, and 7.62 cm. shoe heights are reflective of those mentioned on the literature review but there is no clear description to why the heights were chosen.	A 7.62cm heel is considered high however the thickness of the sole below the forefoot is not given.	An increase in heel height increases forces below the forefoot, increases vertical and anteroposterior forces during walking, significantly less foot abduction angle during support, as well as a greater angle of supination at foot strike (2.3° low, 5.5° high) and a smaller angle of maximum pronation (-7.8° low heel, -4.9° high heel) seen at the rearfoot.
The effects of wearing high heeled shoes on pedal pressure in	1.91 cm low, 5.08 cm medium, and 8.26 cm high. The shoes had different	A shoe with an 8.26 cm heel was considered high, but no reason was given for the	Increased heel height increased the maximum peak pressure below the metatarsal heads, decreased time to maximum pressure, as well as increased the

women. Snow, Williams, and Holmes 1992 [44]	uppers made of different materials and the heel pieces were of different shapes.	definitions of shoe heights.	loading rate to the metatarsal during early support. The increased heel height also produced a more uniform distribution of pressure below the forefoot.
Footbed shapes for enhanced footwear comfort. Witana et al 2009 [36]	Instead of a shoe a profile assessment device was used. This device was able to change the effective heel height in 5 mm increments from 20 to 110 mm. the heel heights chosen were 25, 50 and 75 mm, each of which had a different heel wedge angle based on recommendations of past works.	A height of 75 mm was considered a high heel, this appears to be chosen because of recommendations from last makers.	Increased heel height reduces the comfort experienced however this effect can be reduced by adjusting the heel wedge angle.
Plantar foot pressure during treadmill walking with high-heel and low-heel shoes. Nyska et al 1996 [23]	Participants asked to bring their own shoes including the highest and lowest heel they had worn in the last 3 months. The high heels were between 4.5 and 8 cm and the low heeled shoes were between 1 and 2.5 cm.	No definition, it was the participants discretion	Increased heel height increased the load on the forefoot, and reduced it at the rearfoot, moving the load towards the medial forefoot and hallux. The lateral forefoot showed reduced contact area, forces, and peak pressure. Whilst the medial forefoot had higher force-time and pressure time integrals.
Think high-heels are uncomfortable? Witana and Goonetilleke [45]	A profile assessment device was used instead of a shoe. It was set with a heel height of 75mm but no reason was given to why this was the case.	75mm simulation of a high heel was used.	The results show that there is a footbed shape that one would consider the most comfortable.

Effects of shoe heel height on biological rollover characteristics during walking. Hansen, Dudley, and Childress 2004 [46]	The mid heel shoes were 37 mm (SD = 10 mm) and the high heels were 71 mm (SD = 17 m), the third heel was a no heel condition	The heel height recorded was the difference between the rearfoot and the forefoot sole thickness. The two raised heel shoes were the participants own shoe and were what they deemed to be "mid-heel" and "high-heel" shoes. This was so the participants were already accustomed to the shoes.	The participants adapt their ankle-foot systems to accommodate the shoe's heel height and therefore the rollover shapes do not appreciably change.
Effect of heel height on forefoot loading. Corrigan, Moore, Ch, and Stephens 1993 [47]	Heel placed on a polyurethane form board providing an effective heel heights of 2 and 4 cm and a tubular band was used to provide stable support.	Doesn't call any condition a high heel	The total load under the forefoot was unchanged but the area of the forefoot that remained in contact with the ground was reduced as heel height was increased, which coincided with the load moving towards the medial side of the forefoot.
Effect of heel lifts on plantarflexor and dorsiflexor activity during gait. Johanson et al 2010 [48]	An athletic shoe, an athletic shoe plus a 6 mm heel rise, and an athletic shoe plus a 9 mm heel rise.	No shoe is defined as high.	Between heel-strike and heel-off the medial gastrocnemius mean EMG amplitude increased with both 6 and 9mm heel lifts compared to shoes alone.
Force patterns of heel strike and toe off on different heel heights in normal walking. Wang, Pascoe, Kim, and Xu 2001 [49]	2.5 cm heeled running shoes, 1.3 cm flat leather shoes, 7.5 cm leather high heeled shoes	A heel height of 7.5cm was considered high. This paper does also acknowledge that prior research had considered a 6 cm heel to be high, yet no clear reason is given for using a 7.5 cm heel.	There was a significant increase in total support time whilst wearing high heeled shoes (0.679 seconds in the running shoe, 0.701 second in the high heels)
Changes in temporal gait characteristics and	All shoes are of identical style made by the same	The shoe defined as high was 8.74 cm although no mention	Percentage of weight bearing spent on the lateral and medial calcaneus was decreased when the heel

pressure distribution for bare feet versus various heel heights. Eisenhardt, Cook, Pregler, and Foehl 1996 [50]	manufacture. The heel heights were 1.75 cm (flat), 3.12 cm (low), 5.72 cm (moderate) and 8.74 cm (high)	is made in regards to the thickness of the sole below the forefoot. Mention of previous studies that define a high heel as 6.8 cm, 4.2 cm, 5.08 cm, and 6.88 cm yet no reason is given for using heels of 8.74 cm	height was above 3.12 cm, the percentage of stance spent weight bearing on the fifth metatarsal was reduced in the 8.74 cm heel compared to any other shoe and bare footed. Pressure under the fifth metatarsal head was reduced with increased heel height.
The influence of high heeled shoes on kinematics, kinetics, and muscle EMG of normal female gait. Stefanyshyn et al 2000 [51]	1.4 cm (flat), the following are all defined as high heels: 3.7 cm (low), 5.4 cm (medium), 8.5 cm (high)	All but one shoe was defined as high and then subcategorised. The 8.5 cm high heel was defined as high but the shoes were chosen to represent a systematic increase despite not actually being incrementally increased nor a consistent design.	The active vertical, propulsive and breaking forces were found to systemic increase as heel height was increased. Whilst knee and ankle flexion, soleus and rectus femoris activity all showed a response in a graded fashion to an increase in heel height. The vertical impact force and maximal vertical loading rates were highest for the 3.7 cm heel.
Biomechanical effects of wearing high-heeled shoes. Lee, Jeong, and Freivalds 2001 [37]	0 (low), 4.5 (medium) and (high) 8 cm, the heels were standard block heels. There was no additional information on the shoe.	8 cm was considered a high heel. A survey prior to testing reviled that women felt most “inconvenienced” by heels between 6-9 cm.	Increased heel height reduced the trunk flexion angle whilst tibialis anterior EMG, low back EMG and the vertical movement of the centre of mass increased.
Effect of shank curve of high-heeled shoe on the plantar pressure distribution. Cong, Luximon, and Zhang 2008 [28]	3 inch heels were used	3 inch (7.62 cm) were considered high heels	This was a shank curve investigation and therefore the effects of heel height were not tested.
Different plantar interface effects on	Sneakers and 7 cm high heels	7 cm heel considered a high heel. No reason given for this	Compared to sneakers, high heels increased peak adduction moments at the knee and ankle and

dynamics of the lower limb. Hao et al 2005 [52]		choice.	increased flexion/ extension moments at the hip. High heels produce greater load at the lower limb joints particularly at the knee and hip.
Effect of heel height on in-shoe localized triaxial stresses. Cong, Cheung, Leung, Zhang 2011. [34]	30, 50, and 70 mm high heels. All size 37. Whilst further details on the shoes are not given they appear from the photograph to be of identical designs with the heel height being the only deliberate design feature to change.	All shoes are considered high heels and therefore shoes of 30 mm and over are defined as high heels.	Increased heel height shifted both peak pressure and shear stress form the lateral to the medial forefoot. Increased heel height also increased peak posterolateral shear over the hallux at midstance, whilst peak pressure at push-off reduced.
Foot-ankle roll-over characteristics in different heel heights during walking. Choi, Park, and Kim 2005 [33]	The heels used were 3, 6, and 9 cm. all shoes were the same size. Shoes were chosen for their similar design but no reason is given for the choice of heel height.	All shoes were defined as high heels thus shoes over 3 cm are considered high heels.	Roll-over characteristics did not significantly change with heel height although roll-over trajectories did move downwards in the higher heels. Humans automatically adapt their foot-ankle systems for shoes with heel heights under 6 cm.
Relationship between plantar pressure and soft tissue strain under the metatarsal heads with different heel heights. Ko et al. 2009. [53]	There was a flat condition where the participant stood barefoot, then there were three heel height conditions where the participant stood with wooden block below their heel of 2, 3, and 4 cm thickness.	No condition is defined as a high heel however the purpose of the study is to better understand the effects of high heels.	Plantar pressure increased (from 13.9 kPa to 18.6 kPa) and moved to the first and second metatarsal heads when heel height was increased from 2 to 4 cm. the change in soft tissue strain under the medial forefoot became insignificant for heel heights greater than 2 cm.
Kinematics of high-heeled gait. Opila-Correia 1990 [54]	The participants wore their own shoes. The high heels were 6.1 cm (SD = 0.9)	The average definition was 6.1 cm and this was the judgement of members of the	In high heels participants walked more slowly, from 1.37 to 1.28 m/s, had a shorter stride length, and a higher percentage of gait was spent in stance.

	whilst the other shoes were either low heels or flats and in one case a running shoe, these shoes had an average height of 1.6 cm (SD = 1.1)	public not the scientific community.	Increased heel height also increased knee flexion from 66.1° to 72.1°, hip flexion from 33.5° to 34.8°, and the range of motion of the pelvis in the sagittal plane was reduced from 7.9° to 7.0°.
Kinematics of high-heeled gait with consideration for age and experience of wearers. Opila-Correia 1990 [55]	The participants wore their own shoes. The high heels were 6.1 cm (SD = 0.9) whilst the other shoes were either low heels or flats and in one case a running shoe these shoes had an average height of 1.6 cm (SD = 1.1)	The average definition was 6.1 cm and this was the judgement of members of the public not the scientific community.	Younger participants had increased lordosis of the trunk at heel strike when wearing high heel, whist older participants flattened their trunk. Experienced wearers had increased knee flexion during stance phase when wearing high heels compared to inexperienced wearers. The older inexperienced wearers exaggerated upper trunk rotations.
Effect of positive heel inclination on posture. Franklin et al. 1995 [56]	A 5.1 cm high wooden block was used to elevate the heel of the foot.	Despite clearly listing a number of high heel studies and the heel heights used, there is no reason given for the heel height chosen.	Increased heel inclination lowered anterior pelvic tilt, lumbar lordosis, and sacral base angles.
Effects of heel height on knee rotation and gait. Gehlsen, Braatz, and Assmann 1986 [57]	Barefoot, 1.2 to 1.5 cm heel wedge (running shoe), and 6.0 to 10.7 cm heel wedge (high heels). The shoes were provided by the participants.	The definition of a high heel was 6.0 to 10.7 cm and this was the judgement of members of the public not the scientific community.	Tests completed on a treadmill. Flexion- extension during swing phase reduced from 78.01° (barefoot) to 69.07° (high heeled) and internal-external rotation in swing phase reduced from 9.88° (barefoot) to 6.93 (high heeled).
Long-term use of high heeled shoes alters the neuromechanics of human walking. Cronin, Barrett, and Carty 2012 [8]	Barefoot, and shoes with a heel height of 11 ± 2 cm or 6 ± 1% of stature.	High heels were defined as 11 ± 2 cm or 6 ± 1% of stature. However for their recruitment that required participants to have worn 5 cm heel for 40 hours a week for 2 years and these were also considered to	In long term high heel wearers, walking in high heels there was an increase in muscle fascicle strains and muscle activation during stance phase when compared to that in barefoot walking.

		be high heels.	
The influence of heel height on frontal plane ankle biomechanics: implications for lateral ankle sprain. Foster et al 2012. [7]	Two women's fashion shoes of 1.3 cm (low) and 9.5 cm (high) were used. They were both made by the same manufacture and chosen because they were of a similar design.	9.5 cm is a high heel but no reason given for choosing such a high heel. No mention of the amount of material below the forefoot but the picture reveals that it is very similar for both shoes.	High heels increase ankle plantar flexion and inversion angle. High heels also significantly increase the peak inversion moment and the peroneus longus muscle activation.
The higher the heel the higher the forefoot-pressure in ten healthy women. Speksnijder, Munckhof, Moonen, Walenkamp 2005. [24]	The subjects own shoes were used with heels of 1.95 ± 1.06 cm (low) and 5.91 ± 1.03 cm (high), these were defined as an effective heel height, whilst we can speculate what this means it is not clearly defined in the paper.	A high heel shoe had an effective heel height of 5.91 ± 1.03 cm no reason was given for this height and no details of what the researcher asked the participant to bring was included.	High heels reduced loading under both the midfoot and heel and the contact area as well as the maximum force were both reduced. Walking in high heels produced an increase in peak pressure in the central and medial forefoot, and the pressure time integral increased.
Effect of shoe orthopaedic surgery and research. Edwards et al 2008 [35]	There was a barefoot condition plus wedging was place under the heel to simulate high heel shoes with heel heights of 1, 3, and 5 cm.	The 5 cm heel was described as a high heel and chosen because it agreed with the definition of a high heel in past research [58], whilst the low heel of 1 cm was chosen because past research has defined it as equivalent to a typical shoe in pas research [51]	Increased heel height increased EMG activity in both vastus medialis and vastus lateralis during a sit to stand activity.
Postural influence of high heels among adult women: analysis by	6.5 cm high-heeled platform sandals and 8 cm stilettos both size 35.	Shoe considered a high heel at 6.5 cm but no reason given for this assumption however	The alignment of the right knee was significantly different from the barefoot to stiletto conditions.

computerized photogrammetry. Lunes et al. 2008 [59]		a previous study by the same group is mentioned and it found results with a lower heel. Whilst it mentions that these are platform shoes it does not inform the reader of the amount of material below the forefoot.	
Walking on high heels changes muscle activity and the dynamics of human walking significantly. Simonsen et al 2012 [60]	All participants used a shoe with a 9 cm heel. There is clearly a thick sole under the forefoot. As seen in the picture, but information on its thickness is provided.	9 cm heel defined as a high heel however no reason for this is provided, and this is not the heels effective heel height.	High heels made the knee joint flex more in the first half of stance phase, there was a increase in knee joint abductor moment, and hip joint abductor moment. There was also an increase in knee joint extensor moment.
The influence of heel height on patellofemoral joint kinetics during walking. Ho, Blanchette, and Powers 2012 [61]	1.27 cm (low), 6.35 cm (medium), 9.53 cm (high). All shoes were made by the same manufacture and were chosen because they were a similar design however from the photograph it is apparent that they had different toe boxes and heel designs.	9.53 cm was defined as a high heel but no reason is given for this.	Peak patellofemoral joint stress was increased with an increase in heel height which coincided with an increase in joint reaction force due to higher knee extension moments and knee flexion angles.
The influence of heel height on lower extremity kinematics and leg muscle activity during gait in young	Barefoot, 4 cm heel (low), 10 cm heel (high).	10 cm is defined as a high heel but no reason is given for using a heel that is as high as this.	Increased knee flexion, decreased ankle eversion, and increased muscle activity were all a result of wearing high heels.

and middle-aged women. Mika et al 2012 [62]			
The influence of heel height on utilized coefficient of friction during walking. Blanchette, Brault, and Powers 2011 [63]	1.27 cm (low), 6.35 cm (medium), 9.53 cm (high). The same shoes as the previous paper [61]. It states that the shoes were a similar hardness as assessed by a durometer, it also states that the forefoot and heel outsole patterns were the same across shoes. However from the pictures it is clear that the heel piece of each shoe are different designs.	A high heel was defined as 9.53 cm but no explanation was given for this choice.	Peak utilized friction increased with increased heel height, this was related to an increase in resultant shear force and decreased vertical force.
Moderate-heeled shoes and knee joint torques relevant to the development and progression of knee osteoarthritis. Kerrigan et al 2005 [64]	Two conditions a control shoe similar to an athletic shoe and a test shoe that was the same as the control shoe but with a 1.5 inch heel wedge added.	A shoe of 1.5 inches (3.8 cm) were used but shoes below 2in (5.1 cm) were defined as moderate. This is because it was believed that these would still have an effect despite being lower than those tested previously by the group.	Peak knee varus torques during late stance were greater for heeled shoes. Heeled shoes also produced prolonged knee flexion torque during early stance phase, as well as peak flexor torque.
Gait characteristics and pressure distribution for barefoot and various heel height shoes during walking.	Rubber sole flat shoe, two different high heels with a 4.5 cm and a 9 cm heel respectively. The heels were made by the same	Both the 4.5 cm and 9 cm heel were defined as high heels but no reason was given for the choice of heel height.	The load bearing area of the insole reduced with increased heel height. Pressure at the great toe, medial metatarsal heads, middle metatarsal head all increased with increased heel height but decreased at the lateral metatarsal heads and heel.

Wang and Li 2005 [65]	manufacture and were of identical styles.		
Correlations between biomechanical variables and comfort ratings during high heeled gait. Worobets, Nigg, and Stefanyshyn 2009 [66]	One flat shoe and three heeled shoes. The heeled shoes had heights of 3.7, 5.4 and 8.5 cm	Despite the title of the paper saying it was on high heels none of the shoes are given the title a high heel, instead all the non-flat shoes are named heeled shoes.	Numerous results including: increased flexion at the knee, increased plantarflexion and decreased dorsiflexion and the ankle were all due to wearing high heels.
Preliminary findings from a roentgenographic study of the influence of heel height and empirical shank curvature on osteo-articular relationships in the normal female foot. Schwartz and heath 1959 [67]	There were two subjects and each had their own heel heights that the tested in shoe, barefoot but standing on shoe heels of the same height as the shoes, and standing barefoot but elevating the heels to the correct heights. For subject 1 the heights were 0, 6/8, 9/8, 12/8, 17/8, and 21/8 of an inch, whilst subject 2 used 0, 5/8, 12/8, 13/8, 14/8, and 17/8 of an inch.	A large rage was used to establish the trend from flat to a high heel.	The foot distal to the first metatarsal head does not change with heel height, the shortening of the heel-to-ball length of the foot when shod may increase to twice that seen when bare foot, this shortening is due to the evaluation of the longitudinal arch and the shoe shank, accompanied with the hinging of the foot at the cuneonavicular and talonavicular articulations.
Thinking while walking: experienced high-heel walkers flexibly adjust their gait. Schaefer and lindenberger 2013 [13]	Two shoes: gym shoes and a high heel with a 6.1cm heel and a heel area of 4 cm^2. The participants were of numerous sizes.	A 6 cm heel was considered a high heel. Whilst much past research was reviewed a clear reason for the choice of heel height was not given.	High-heel experts adapted walking regularity more flexibly to the shoe worn and the cognitive load than the novices.

3D foot shape and shoe heel height. Kouchi and Tsutsumi 2000 [68]	Flat surface, simulated heel of 4 cm, and 8 cm	No clear reason given for heel heights they are just intended to cover the common range of heels.	Increased heel height medial and lateral arch lengths and foot breadth reduced. If the distal half of the section of the foot between the metatarsal heads and the heel became higher, narrower, rounder and rotated anti-clockwise in the anterior view. The medial inclination of the heel reduced, the foot became less outflared, and the overhang of the navicular became less visible.
Kinetics of high-heeled gait. Esenyel, Walsh, Walden, Gitter 2003 [69]	Low-heeled sports shoe with a 1 cm heel, a high-heeled dress shoe with a manmade upper, a rounded toe box with a heel height of 5.5 cm and a heel width of 6 cm.	A heel height of 5.5 cm is considered a high heel.	High heel significantly reduced the ankle plantar flexor muscle moment (1.56±0.13 versus 1.34±0.20 N•m/kg), power and work (0.34±0.17 versus 0.25±0.08 (unit not given but assumed joules)) during stance phase. Conversely there was an increase in work for the hip flexor muscles in the transition from stance to swing phases when the high heel was worn. Furthermore there was a reduced effectiveness of the ankle plantar flexors during late stance. Larger muscle moment and increased work were required at the knee and hip, which the authors suggest could predispose long-term wearers of high heels to musculoskeletal pain.

2.1.1. Technical definitions of heel height

The literature suggests that a heel of 6 cm or over can be called a high heel, however it is not clear what features or physical components of the shoe are measured as 6cm. There are various technical definitions of heel height that should be adopted to underpin the definition of “high” heeled shoes. One of the more detailed standards is the European and British standard (BS) BS EN ISO 19952:2005, which defines heel height as “– *height of the heel measured vertically from the floor to the top of the heel at the back, including the top piece*.” The difficulty with this definition is that it relates only to the dimensions of physical shoe heel components rather than position of the foot. It is therefore relevant only to manufacturers rather than those interested in how footwear designs affect foot biomechanics and foot health. This definition does not take into consideration the mechanics of the foot or the geometric constraints the shoe is producing for the foot. One such example is shown in Figure 3, where both shoes have the same heel height according to BS EN ISO 19952:2005 but the effect on foot biomechanics is quite different because the *Last Contact Point* differs. In shoe A, with a longer *Last Contact Point*, the angle between the midfoot and the ground is less than in shoe B. This will result in a change in the load applied to foot structures.

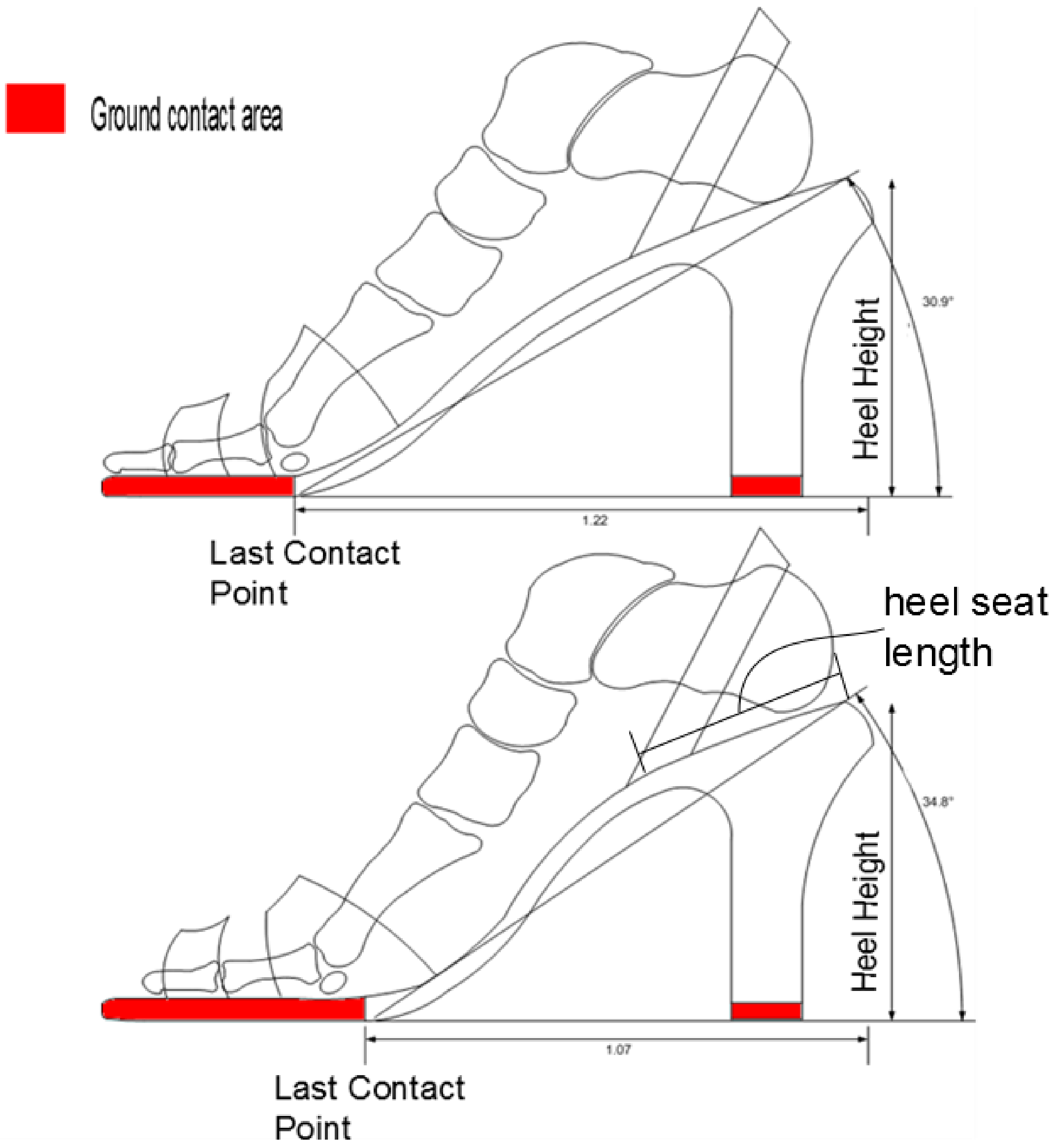

Figure 3: The effects of last contact point location, when heel height is fixed.
The red areas show the regions of the shoe which are in contact with the ground. Horizontal measurement shows the last contact point distance and the angle shows the projection angle from the apex of shoe to highest point

Other important features such as the amount of material under the forefoot are also not included in the British Standards. Thus, a platform shoe could be said to have a heel of 5cm according to BS EN ISO 19952:2005, when infact the material under the forefoot is also 5cm, and subsiquently there is no height differentiatial between the heel and forefoot. To prevent confusion between the height of the manufactured heel piece and the difference between height of the heel and forefoot from the gound, the term *effective heel height* [24] has been advocated. This is similar to the American definiton of heel height, which is the height of the *breast point of the last* [38], where the breast point marks the distal end of the *heel seat*. The defintion from the American system is the most accurate and consistent of all heel height definitions provided, because it takes the measurement from the last. Taking the measurement from the last effectively normalises against features such as sole thickness and reduces measurement error because many measurements are predefined by the last maker and the remainder are taken from marks left on the last. However, many research studies do not have easy access to the lasts of the shoes they study and therefore attaining and reporting this mesurement and a clear definition of heel height may prove impossible.

The effective heel height [24] would therefore seem the most anatomically and functionally relevant definition of heel height. However, it still does not provide a full description of the foot position. In fact, it only tells us the difference in the vertical position between the forefoot and heel. Whilst this is of interest it has also been shown that for a given heel height shoe features such as *heel seat angl*e can influence the position of the calcaneus and this can also affect pressure [36]. It would therefore be beneficial if *heel seat length, heel seat angle, last contact point,* and *last depth* (which are all clearly defined later in this chapter) were included in a definition of heel height. This would provide a more detailed account of the foot's position using shoe features that have been shown to affect plantar pressure. However, accessing these values requires cooperation with footwear manufacturers so that all aspects of the shoe geometry can be specified. This co-operation is not always available to researchers especially when their research is conducted independent of the footwear manufacturer whose footwear they are investigating.

Overall there is a difficulty in defining what a high heeled shoe is. Furthermore, definitions in the literature have not generally complied with technical standards of heel height. The result is a difficulty in understanding precisely what footwear and what heel heights have been investigated previously, and whether in fact “high” heels have been investigated at all, or if other features of the shoes tested were in fact the reasons for the results observed.

2.1.2. Common types and variations of high heeled shoes

As well as the height of the heel, footwear in the “high heeled” genus can be further classified dependent upon the shape and style of the material added below the foot heel, or the design style or material of the upper. The heel categories include: wedge, stiletto, block, tapered, blade etc. (Figure 4 and Figure 5), whilst upper types include: sandals, open toed, close toed, with and with out straps, with and with out arch support provided by the upper in the midfoot (Figure 6). Each of these variations has the potential to affect the foot biomechanics of the wearer. For example, a wedge heel and stiletto heel each have different contact areas with the floor and the foot. This could affect load transmission to the foot but also the stability of the wearer. Uppers with or without material to brace the toes or mid foot will provide different levels of constraint on movement of the foot inside the shoe. Thus, understanding upper style and properties as well as heel height and heel style are all relevant to foot biomechanics, foot health and comfort.

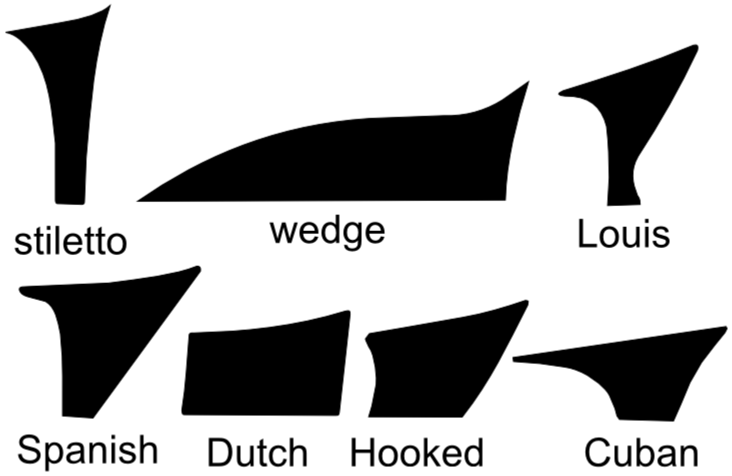

Figure 4: Comparison of the most common heel shapes.


Figure 5: Types of high heel.
(From top left to bottom right: wedge, stiletto, block, tapered, and blade)

Figure 6: Types of Upper Design
(Top left: sandal or strappy, top middle: open toed pump, top right: closed toed pump, bottom left: ankle strap, open toes, bottom centre: ankle strap closed toed pump, and bottom right: closed-toe pump with arch support)

Besides heel height, the two aspects of the heel that are most likely to affect the foot are the contact area between the sole of the heel and the ground, and the position and shape the foot is manipulated into by the shoe. Some researchers have also observed that ground contact area under the heel and forefoot can affect plantar pressure [23, 43]. However, few studies of “high heeled” footwear detail or even mention these features when describing the footwear they investigated. The failure to adequately and precisely specify the footwear tested is a significant barrier to understanding the relationship between footwear design and effects on foot biomechanics. Without detailed characterisation of the footwear geometry and materials, as well as independent control of these features across multiple experimental conditions, it is impossible to know what aspect of the footwear design is responsible for any observed effects on feet or gait (e.g. changes in plantar pressure). Likewise, providing information on the sagittal plane angle at which the heel of the foot is raised from the ground is not common.

Not defining the sagittal plane angle seems an important omission in much of the footwear literature given that Hicks [31] proposed that the onset of the windlass might occur when the hallux is extended by 10 degrees, not when the heel or toe were raised a predefined height above the forefoot (whilst the windlass relates to the plantar fascia, the concept is transferable to the multiple long and short muscles inserting into the plantar surface of the toes). One explanation for this omission is the difficulty in defining the shape of the *footbed* posterior to *the last contact point*, due to the many components that are combined to create the final shape. Footwear lasts have a number of features affecting midfoot orientation including: *last depth, heel seat length*, and *heel seat angle*, but the footbed can also have characteristics which will affect the final position of the rearfoot.

To further add to the complexity in defining and investigating high heeled footwear in a transparent way it is important to acknowledge that *heel wedge angle* [36, 70], upper design and materials [71], *heel seat length* [36], *heel cup* [72], *arch support*[72], *last flare* [73] and *insoles* [72] might also affect foot biomechanics and gait (these features are explained in more detail later in this chapter). Furthermore, many other shoe features, including *heel flare* [74] and *toe spring angle* [75], affect wearers walking in non-high heeled footwear, and it is reasonable to assume they will also affect wearers of high heels. Thus, all features of the footwear should be defined when investigating footwear effects on gait so that the footwear being tested is fully characterised and understood. However, with the large number of possible variables and the possibility that future investigations discover a new footwear feature to be important, to provide a truly definitive list of features may not be possible. Thus an investigator should strive to report as many footwear features as possible and all remaining footwear features should be kept identical to ensure any confounding effects are minimised.

In summary, this thesis is concerned with the effects of heel height and related footwear design features on the foot. Heel height is not consistently defined nor reported in the prior literature. On the assumption that the effect of shoe heel height on foot behaviour is of interest, “effective heel height” seems the most appropriate definition to adopt. The effective heel height is the difference in height between the plantar surface of the forefoot and the plantar surface of the heel. What constitutes a “high” heel has likewise not been well defined, often because of poor reporting of the shoes being investigated. Since previous research has recommended that shoes over 5.06 cm should not be worn to reduce the risk of injury [27], for the purpose of this thesis a high heeled shoe will be considered as a shoe which has an effective heel height of 5cm or more, until such time that results suggest otherwise.

2.2. Anatomy of high heeled shoes

As previously discussed, many footwear features have the potential to affect foot and lower limb biomechanics and foot health. In this section key footwear features relevant to high heeled shoes, are defined and where there is appropriate evidence, their effects reviewed. The following is broken into two sections, the first focuses on the features of a pattern, called a last, around which the shoe maker builds the shoe. The last is responsible for much of the design and fit of the shoe. The second section is focused on the outer sole and heel section of the shoe which are made separately from the rest of the shoe and then added towards the end of manufacture.

2.2.1. Key features of the footwear last

Features of the footwear last ultimately describe the landmarks and geometry inside the shoe since it is around the last that the shoe upper and soles are formed. However, how these features relate to footwear comfort and foot health are complex because many last features are interdependent. Whilst some last features may not be directly linked to comfort and foot health (general last features), their definition is a prerequisite to defining and understanding last and shoe features that are directly related to comfort and foot health. For this reason general last features and those specifically related to foot health are both included in the following section.

Whilst there are many dimensions used in shoe-last making most are defined by the American Footwear Manufacturers association. There are however two main last-dimension systems, the first is called the Chinese system and although more detailed of the two systems it is not as widely used. The second system is called the AKA64 which is a shoe last developed by German shoe manufactures who used extensive foot measures to improve footwear fit. It is only in the AKA64 system that forefoot angles are used.

4.3.1.1. General features of footwear lasts:

Feather line or feather edge:

This separates the top surface of the last from the bottom surface. It is a visible line or edge that traverses around the entire last circumference, as shown In Figure 7. Other key features of the last are defined as specific points along the feather line, including the heel point, and last bottom centre line.

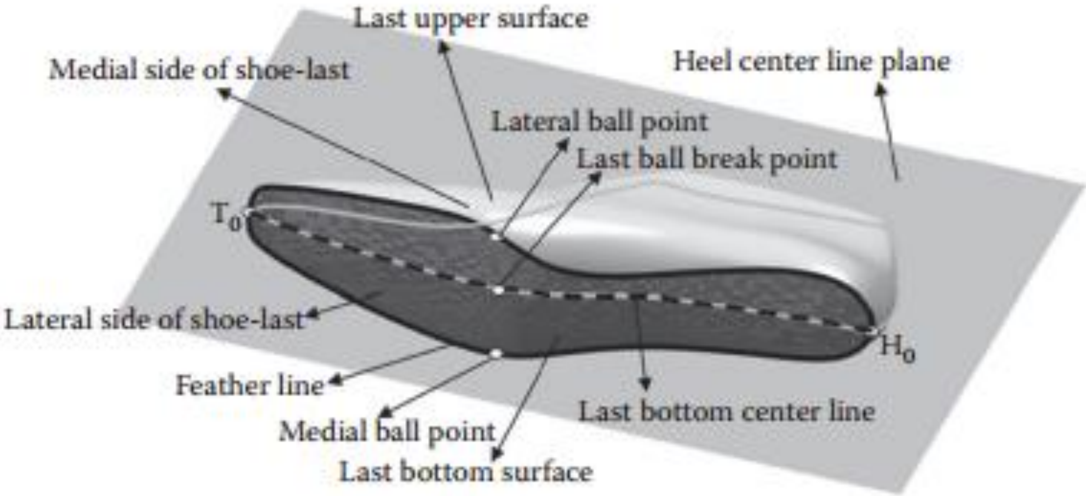

Figure 7: shoe-last centre line and related features [38]

Heel point (H_0):

This is the rear most point of the heel on the feather line, as shown in Figure 7. Along with the toe point (T_0) the heel point is used to define the last centre line plane, last contact point, and heel seat length.

Cone length or heel top length

Different authors may call different features, the last cone [38, 76], but for the purpose of this thesis the definition used by Luximon and Luximon [38] has been adopted. The last cone is the flattened surface on the top of the last in the region of the ankle as shown in Figure 8. If C_1 and C_2 are the most distal and proximal points of this aspect then the cone length is the distance between points C_1 and C_2, (Figure 8). In conjunction with the Heel Point, the cone length is used to define the last centre line plane.

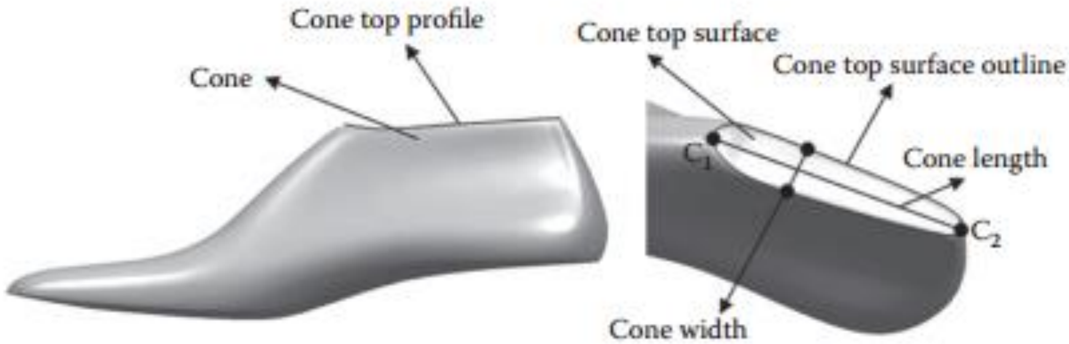

Figure 8: cone of the shoe-last [38]

Last centre line plane:

This is a plane that divides the last into its medial and lateral sides. This plane is correctly positioned when it passes through points H_o, C_1 and C_2. The plane is used to define the bottom curve, as well as the medial and lateral forefoot angles.

4.3.1.2. Last features that may affect comfort and foot health:

Bottom curve or last bottom centre line curve:

This line represents the intersection between the last centre line plane and the bottom surface of the last, Figure 7. This defines the geometry of the last bottom and thus is a primary factor in the position of the foot inside the shoe. It is often broken up into separate regions including the heel seat, the cuboid region which has the shank curve incorporated into it, as well as the toe spring (shown in **Figure 9**), which have independently been shown to affect pressure and comfort scores [36] and are discussed in more detail below. The bottom curve is used to define the last contact point.

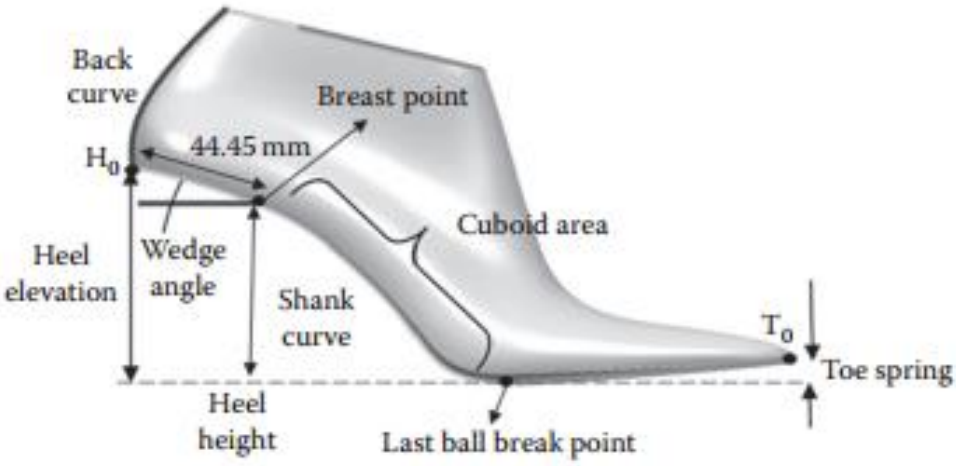

Figure 9: Shoe last side view [38].

<u>Last contact point or last ball break point (Figure 7):</u>

When the last is laid on a flat surface the Last contact point is the location upon which the forefoot of the last will contact the flat surface. In this position the last will rest along a line traversing medial/ laterally at the forefoot. The last contact point is then the bisection between this medial/lateral line and the last centre line plane. It is from this point that the toe spring angle and the last depth originate, these are critical to the position of the foot and toes inside the shoe [77]. Generally the toe spring is changed when either the sole material or heel height is changed. The harder the sole the more toe spring required, whilst higher the heel the less toe spring required [38]. The toe spring can have significant effects on plantar pressure and as a result has been the focus of literature on diabetic participants [77], for whom high plantar pressure can be detrimental to foot health.

Last Depth (shank curves):

The last depth is the sagittal plane shape of the underside of the last in the middle to rear section of the last bottom centre line curve. A shallow last has little to no curvature in the sagittal plane of the midsection of the foot, whereas a deep last will describe a deep arch. The last depth can also be called the shank curve and some examples of these shapes were provided by Goonetilleke [38] as shown in Figure 10.

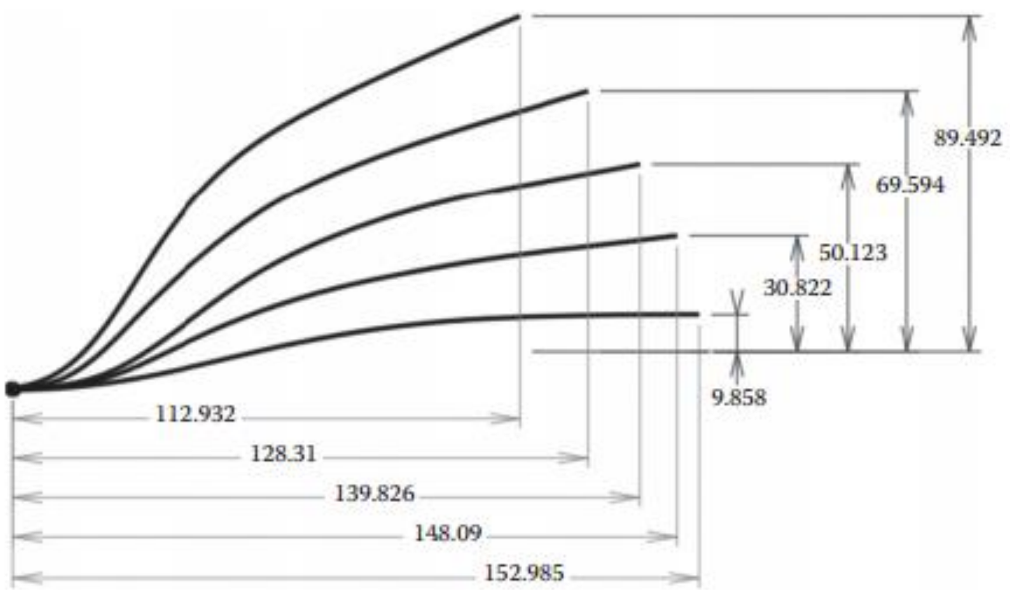

Figure 10: Shoe-Last shank curves
(values shown are an example of those used for shoe size 36, the length of all the individual curves are 155mm), the point to the left represents the last contact point and the right side represents the plantar heel surface [38]

An increase in Last depth has been shown to decrease the pressure time integral in the forefoot, and increase it in the mid and rear foot regions [28]. The same study has shown that the higher the last depth the lower the peak pressure in the forefoot region in the midstance phase. They also summarised that because there was increased arch support for increased last depth the pressure time integral, the peak pressure, and the peak contact area in the midfoot region all increased, these results can be seen in Figure 12, Figure 13, and Figure 14. Shank curve is a feature that is normally changed when heel height is increased; the results shown highlight that shank curve is an important factor in pressure investigations of high heeled shoes.

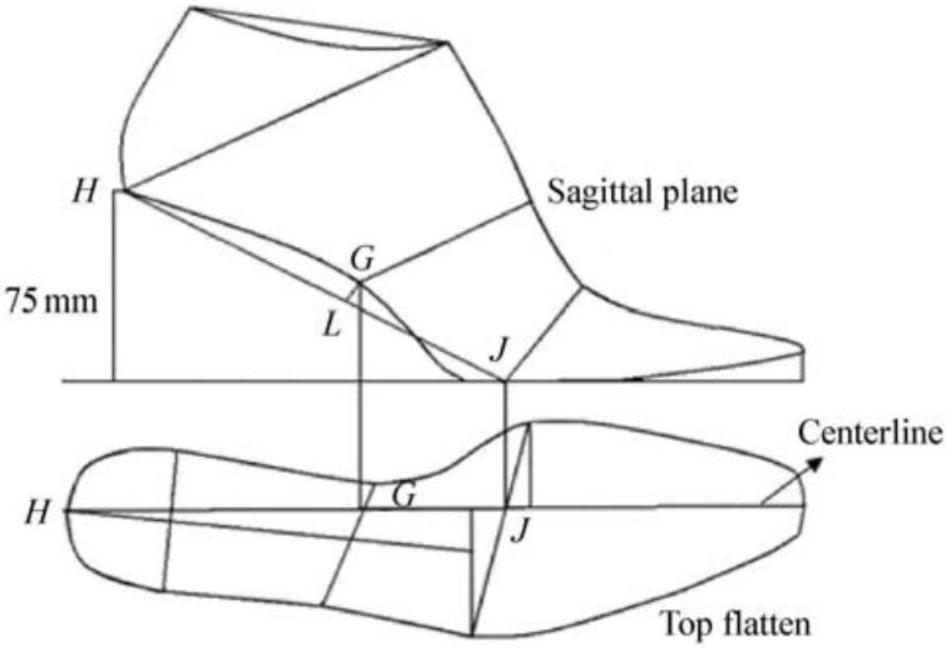

Figure 11: diagram showing the definition of GL taken from Cong et al 2011 [78]

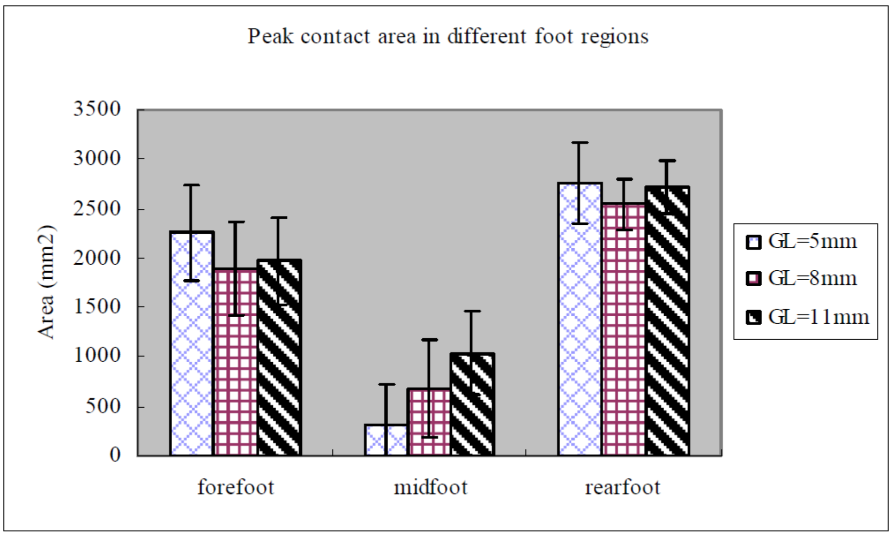

Figure 12: The peak contact area for a range of foot regions, using varied shank curves. GL represents the distance from the waist of the last to the line joining the heel breast to the ball tread. Taken from Cong et al [28]

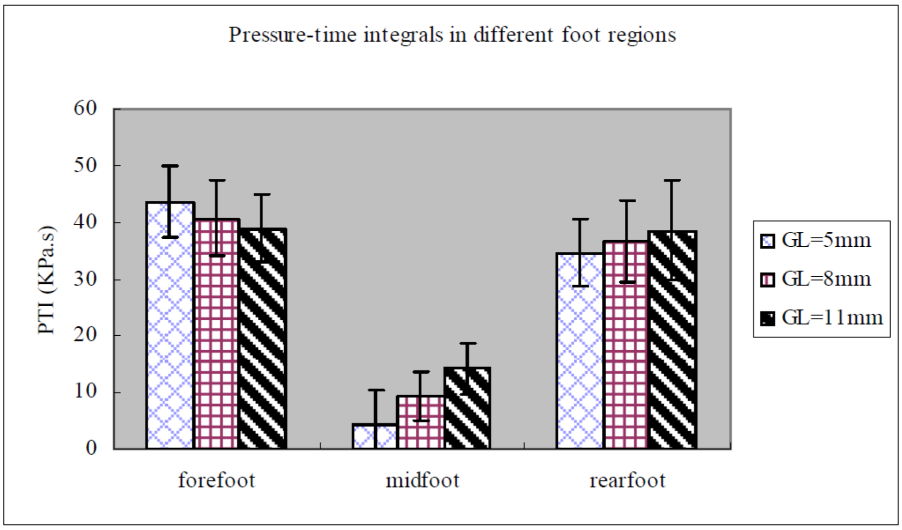

Figure 13: The pressure-time integral in the different regions of the foot under a range of shank curves.
GL represents the distance from the waist of the last to the line joining the heel breast to the ball tread. Taken from Cong et al [28].

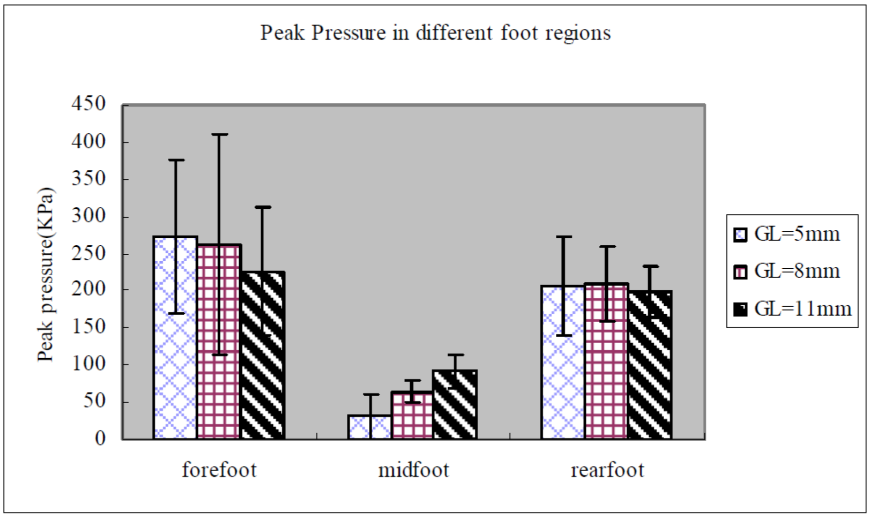

Figure 14: Peak Pressure in the different regions of the foot using a range of shank curves.
GL represents the distance from the waist of the last to the line joining the heel breast to the ball tread. Taken from Cong et al [28].

Last flare:

The last flare is the longitudinal curvature of the last viewed in the anatomical transverse plane of the wearer. Often referred to as either a straight or curved last, this feature is principally the transverse plane curvature of the forefoot of the last relative to the rearfoot. Varying significantly between different last manufacturers this can often be the key feature that affects both comfort and fit in all shoes, including high heels. The mismatch between the shoe and foot flare is said to be a primary factor for discomfort in the ball region as well as the formation of bunions [73]. Moreover, the same investigator states that if there is not perfect fit between the shoe curvature and the foot, the forefoot will be deformed. If the shoes are only worn for the short term then this deformation will be temporary but if the shoes are worm for a long time this deformation could become permanent [73].

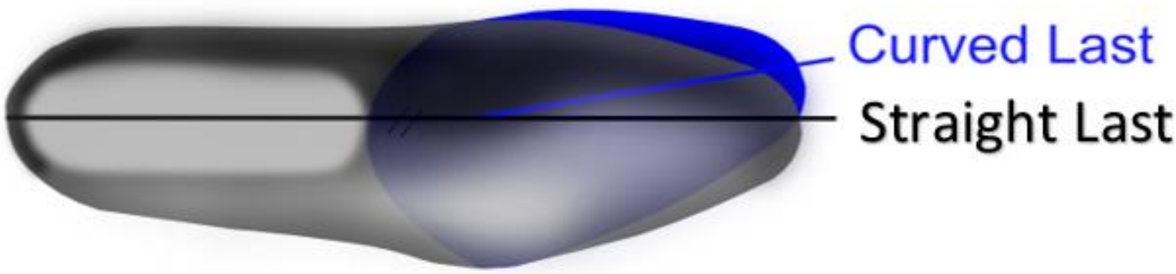

Figure 15: Last Flare
(grey scale is a straight last and in blue is the curved last)

Heel seat length:

The heel seat is the region at the back of the shoe and holds the heel in place, providing a flat platform upon which the sole of the foot heel rests. The sagittal plane length of the heel seat is called the seat length. One end of the seat length is the rear most point of the heel, the other end is the location where this flattened section ends and the curvature of the midfoot section begins to angle down towards the forefoot. The point at which the decent down to the forefoot begins is called the breast point, as shown in Figure 16 and **Figure 9**. The heel seat length is often defined as the distance between the H_o and the breast point, however, the breast point is arbitrary and thus solely dependent upon subjective judgement made by the last maker. It has been shown that adjusting the heel seat length can effectively reduce the heel pressure and impact force [42] and similarly affects due to the seat length have observed on perceived feeling which can be clearly seen in Figure 17 where the two lines show the difference between the two different seat lengths.

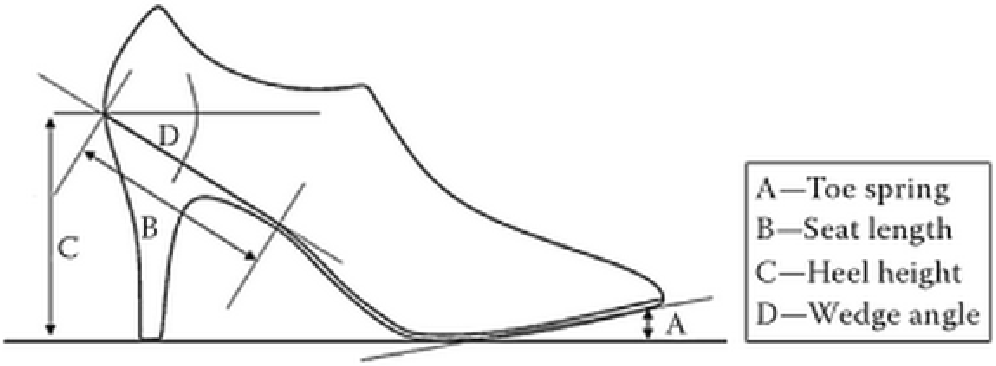

Figure 16: Footbed parameters [38]

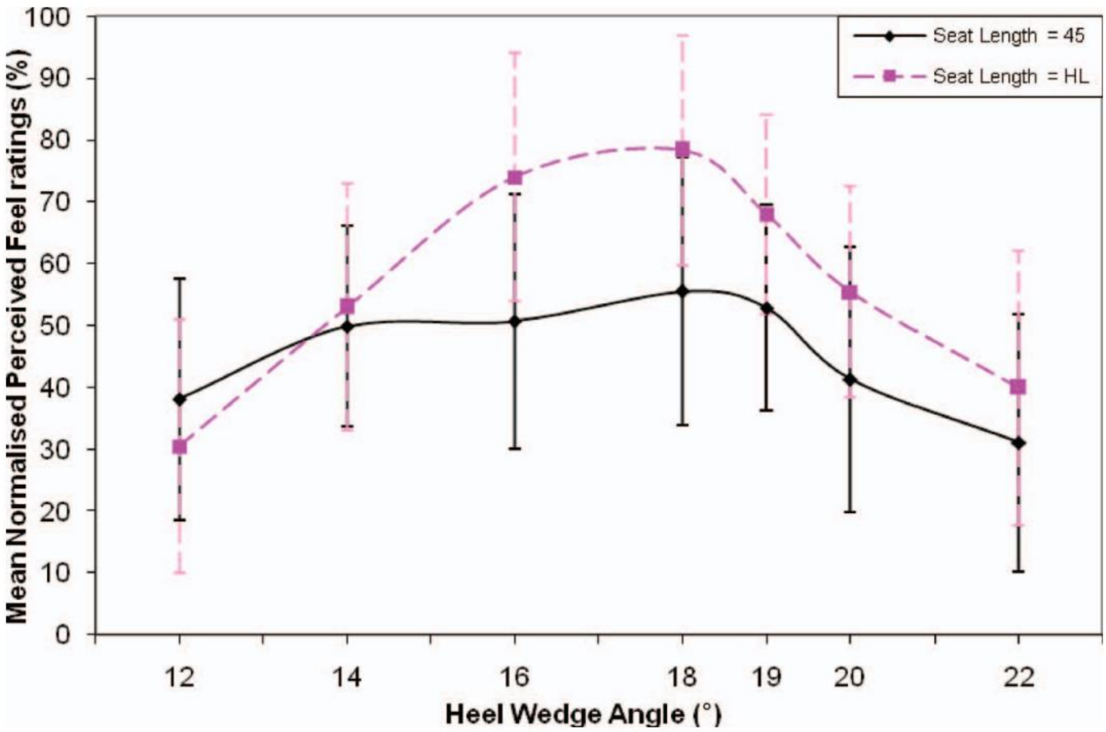

Figure 17: The effect of Heel wedge angle on perceived feeling
The mean normalised perceived (overall) ratings against the heel wedge angles at 75 mm heel height [36]. HL = the distance from the pternion to the fifth metatarsal head minus the distance from the pternion to the point where the foot first touches the ground.

Medial forefoot angle:

The medial forefoot angle is the angle between a line originating at the most medial point in the shoe apex region (M1 Figure 18), parallel to the last centre line plane, and a line connecting M1 to the medial aspect of the start of the toe allowance section of the shoe. This angle describes the narrowness of the toe section (toe box) of the shoe. A narrow toe box or in fact a toe box of reduced volume, in high heeled shoes has been blamed for the discomfort and poor health of the toes in regular wearers [44].

Lateral forefoot angle:

The lateral forefoot angle is the angle between a line passing through the point tangent to the most lateral point in the shoe apex region (M2, Figure 18), parallel to the last centre line plane and a line connecting M2 to the lateral aspect of the start of the toe allowance section of the shoe. This is the lateral version of the medial forefoot angle and also has a relationship with the narrowness of the toe box area and the volume of the forefoot area of the shoe. It has been shown that shoes with a rounded toe box produce the least pressure on medial aspect of the toes whilst a pointed toe shoe showed the least pressure on the lateral sides [79].

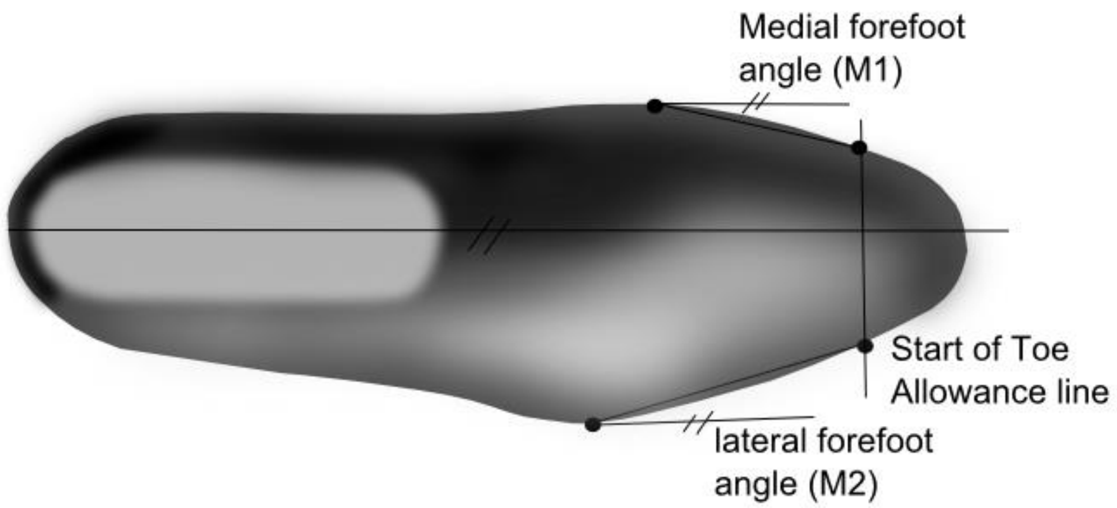

Figure 18: Last forefoot angles

Last ball girth:

The last ball girth is the circumference of last at the last contact point, which incorporates M1, M2 and the last contact point (Figure 19).

Changing the two forefoot angles and/or the last ball girth could lead to compression of the toes which will increase the recorded value of pressure in the forefoot region [79] (it is impossible to increase the compression without increasing the pressure as one directly affects the other). Morten's neuroma (thickening of nerve tissue between metatarsals 3 and 4) is associated with compression of the inter-digital nerves and has therefore been linked to compression of the forefoot. Adjusting these forefoot features may have a direct effect on foot health if it was to reduce nerve tissue compression [4, 80].

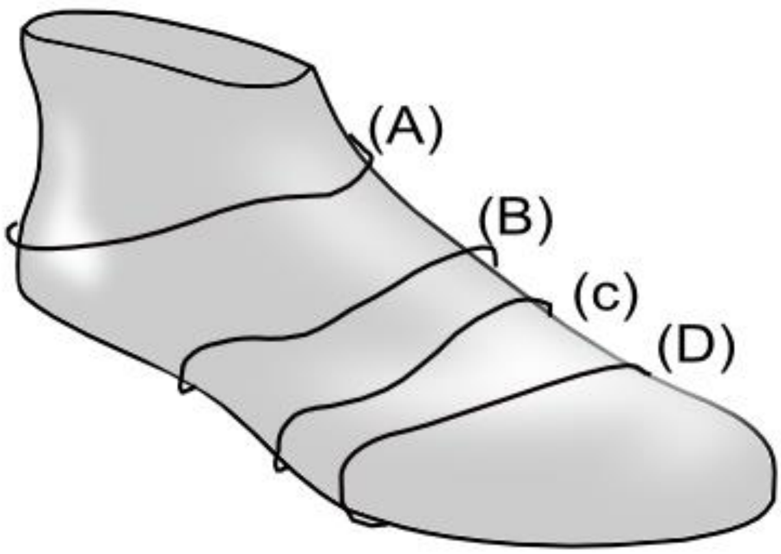

Figure 19: Last girth measurements
A: heel high instep girth, B: last medium instep girth, C: last ball girth, D: waist girth

Last medium instep girth:

The last medium instep is the circumference of the last at the instep and is the smallest girth in the mid foot section of the last, (Figure 19). This provides us with information that can be linked to the fit of the shoe by comparing the difference between this measurement on the foot and the last.

Heel-high instep girth:

The heel-high instep girth is the shortest perimeter around the back of the foot and includes the rear most point of the last (pternion point) and the top surface of the foot in front of the ankle (Figure 19). This is a common measurement to compare the fit of shoes.

Waist girth:

The waist girth is the circumference around the last at the approximate centre of the metatarsal heads, measured in the last centre line plane (defined previously in this chapter). This is very similar to the last ball girth and thus variation in between these two girths might be expected to have similar effects. This measure has also been included here because past researchers have used both waist and last ball girth measures and it is useful to be aware of differences in their definition, even if their effects may be similar.

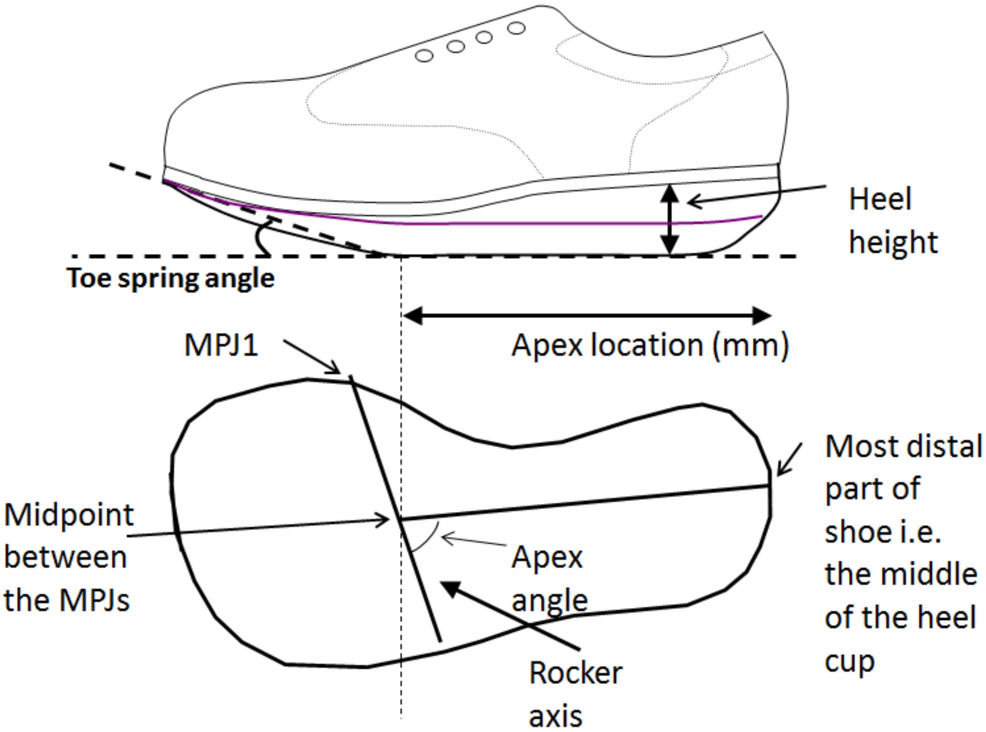

Figure 20: Features of the shoe
(image adapted from that shown in Chapman et al [77])

Toe spring angle:

This is the sagittal plane angle between the forefoot section of the last and the ground in the last centre line plane. For most shoes this is the same for both the last and the shoe, however when there is wedging under the forefoot it is possible that the sole design can change the amount of toe spring from that originally incorporated into the last. In all shoes this affects the natural gait pattern but for high heels it can be particularly important because when heel height is increased the toe spring angle will subsequently need to be changed, to ensure the toes can remain in contact with the ground. It has been stated that the role of the toes is to relieve the metatarsal heads of some of the pressure exerted on them [81] which is only possible if they are able to exert a load onto the ground. The amount of toe spring is however related to both sole material and the heel height. A harder sole will require a greater toe spring, whilst the higher the heel the less toe spring required [38]. This angle varies considerably between footwear and many heel height studies appear not to have controlled for this feature nor reported it and thus their results may be adversely affected.

2.2.2. Key features of the sole and heel of the shoe

Sole thickness:

This is the total thickness of all materials between the floor and foot in the forefoot region. In high heeled shoes this thickness is important because it reduces the effective heel height that is created by a tall heel component on the rear of the shoe. Increased material under the foot is also likely to increase the weight of the shoe and affect the stiffness of the shoe, which will ultimately affect the propulsive impulse [82]. Past research has also shown that thin soled shoes produce an increased plantar pressure and a decreased plantar comfort [83].

Apex location (or apex position):

When the shoe is rested on a flat surface and observed from the sagittal plane, the apex location exists on the long axis of the shoe, where the forefoot is in contact with the ground. When looking at the plantar surface of the foot, the apex location appears as line passing across the metatarsal heads as shown in Figure 20. It differs from the last contact point because the apex location is a feature of the sole of the shoe not the last. Past research has shown that this can vary the natural gait motion, and reduce plantar pressure, as a result it has been a focus of studies concerned with people who have diabetes [77]. Results in low heeled shoes show that the best location for the apex to reduce forefoot pressures is 55 – 60% of shoe length [84, 85]. This point has also been called the sole flexion point, the primary difference being that the sole flexion point is measured relative to the metatarsal-phalangeal joints (MPJs) instead of a percent of foot length. Investigations on the sole flexion point have shown that if it is located proximal to the MPJs, plantar pressure at metatarsal-phalangeal joint four and five (MPJ 4-5) will be increased by 6.2% [86]. In high heeled shoes there are no results that are as conclusive as those in low heeled shoes, likely due to lack of investigative studies on this feature. However, with such clear effects on the foot in low heeled shoes, this feature should be clearly reported and understood and it needs to be maintained across test shoes.

Apex angle:

This is the angle between the last bottom centre line curve and a line joining metatarsal phalangeal joint one to five (MPJ1 to MPJ5), projected onto the transverse plane (Figure 20). On a shoe or last the MPJ1 and MPJ5 points are equivalent to the most medial and lateral points of the forefoot section. Much like the Apex location, this has been shown to affect plantar pressure distribution in low heel shoes, and therefore has received interest from studies on diabetic footwear [77]. Despite its importance in diabetic footwear research, no such study has been found that investigates this same angle in high heel footwear.

<u>Distal heel flare or flaring of the sole geometry:</u>

This is the distance between a vertical straight line which touches the rear most point of the shoe and a vertical line which touches the rear most point of the heel piece at the shoe-ground interface, as shown in Figure 21. This is often expressed as the angle, the rear of the sole projects out behind the foot, as shown in Figure 22 as the "heel flare". However, in high heels the location of the contact between the heel and the ground is moved forward under the foot to provide a base of support under the foot during quiet standing.

Figure 21: Distal Heel Flare

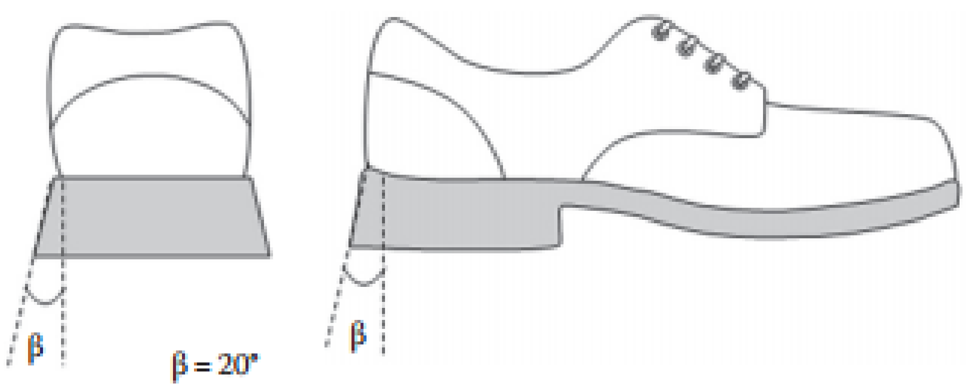

Figure 22: Heel flare [87]

Sole-ground contact area:

This is the total area of the sole that is in contact with the ground during quiet standing. This includes the area of both the heel and the forefoot. This contact area can be affected by the heel design, the apex position, the apex angle, the forefoot angles, the toe allowance, as well as other shoe features. It is important because the amount of area available to absorb load at this interface will affect the way it is distributed at other boundaries such as the shoe-foot interface, and thus pressure applied to the foot. Changing this contact area will also change the level of friction between the shoe and ground which will affect the risk of slipping [88]. High heeled shoes significantly reduce the size of this area by removing contact between the shoe and ground in the midfoot and heel regions, as can be seen in Figure 23. The effect of reduced contact area at the midfoot and heel is that the majority of the loading that the foot exerts onto the ground has to pass through the forefoot, increasing the loading on the foot in corresponding foot regions. The reduced base of support may also significantly reduce stability during gait and quiet standing, the results of which have lead past researchers to conclude that when heel height is high mediolateral stability becomes more important to the wearer than the natural motion of calcaneal eversion [27].

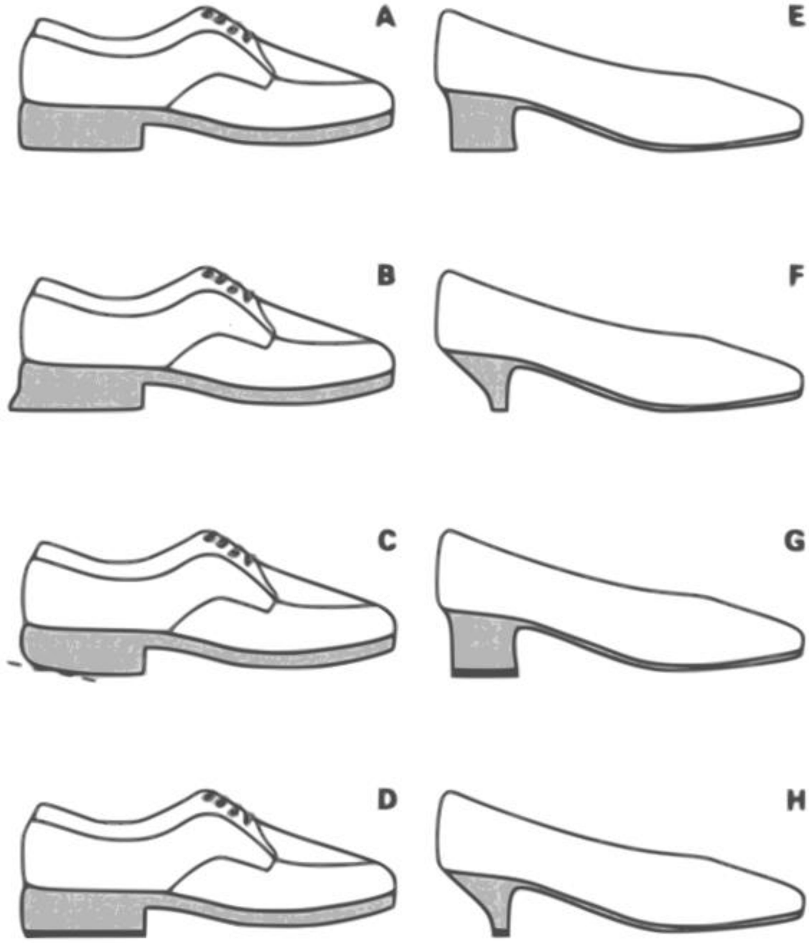

Figure 23: Sole design and ground contact area [41].

2.2.3. Key features of the upper

Upper design:

The purpose of the upper is to hold the shoe onto the foot and the most rudimentary designs, such as those seen on flip flops and sandals, are little more than a strap that hooks onto the toes. A shoe upper consists of the material that covers the top of the foot and is joined to the sole (traditionally by sewing but glued in many modern shoes). The design of the upper can affect where and how loads are applied to the foot, as well as the positioning of the foot in the shoe [73]. A change in the upper design will subsequently affect the relationship between the foot and sole since the upper constrains the foot against the sole. It follows that upper properties (geometry and material properties) will likely affect loads between the sole and foot (plantar pressure). Evidence of the effect of uppers on plantar loading has been sought by comparing sole wear patterns in shoes with a loose fitting upper to those with a more traditional closed and stiff upper. In the latter, heel wear occurs on the lateral side, whereas it occurs on the medial side when uppers are loose or absent [73].

Whilst the comparison of open shoes and closed shoes is an interesting observation, there are many differences other than upper design between flip flops and shoes with complete uppers, and thus no clear conclusion is possible because prior research has not isolated the upper as an independent variable. Furthermore, nor has past research indicated what property of the upper (its geometry or its material properties) are exerting the greatest effect. However, the upper may restrict the foot's movement ensuring the foot makes contact with regions of the sole it otherwise may not, it could also constrict the foot if the internal volume of the shoe is smaller than the foot (tight fitting upper), this may compress the foot into the shoe sole (via the footbed). The result of this change could increase plantar pressures. However, this effect is also dependent upon other upper material properties which are reviewed below. It should also be noted that the upper material is important in the gas transfer from inside to outside the shoe. Failure to allow adequate movement of air can lead to increased temperatures which in turn cause the foot to expand in volume, further increasing the constraining effect of the upper on the foot

As well as its biomechanical function, the breathability of the upper material can affect the humidity inside the shoe. This can lead to skin problems such as rashes, fungal infections, maceration and skin breakdown [89]. Thus the upper design and properties are instrumental in maintaining comfort of the foot during gait but also preserving general good foot health.

There are constraints imposed on uppers that limit what is possible in terms of modifications to improve comfort and pressure. Often the upper of the shoe is essential to the shoe's aesthetics and includes unique features that consumers recognise as part of the brand identification. The most well-known of these examples is the Adidas three stripes. The three stripes were first used in 1941 (although not patented until 1949) with the purpose of supporting the foot [74]. Whilst they may not be essential for support in a modern shoe, customers loyal to the Adidas brand will expect them to be included in the design.

Upper material stiffness

Increased upper stiffness in the toe box can result in blisters, corns and prevents the foot from flexing normally [89]. The shape of the toe box can significantly affect plantar pressure, with pointed toe boxes shifting pressure medially under the forefoot. Branthwaite et al. found that whilst wearing round toed shoes the pressure on the medial side of the toes was 40.2(0.31)kPa compared to 51.97(0.43)kPa in pointed shoes. The opposite occurs on the lateral side, with pressure increasing from 60.8(0.43)kPa in pointed shoes to 73.54(0.47)kPa in the round toed shoes [79].

The upper design can constrain the foot but its ability to do so is affected by the stiffness of the upper material. Furthermore, many materials that are used for shoes such as leather and suede have a different stiffness depending on their orientation. Shoe manufactures are aware of this and take care to orientate the material appropriately during the manufacture process. For example, the angle of a piece of leather might be adjusted to ensure it flexes with the foot in one direction whilst resisting deformation of the foot in another. The proximal / distal stiffness is, therefore, the resistance of the material to deformation when loaded at the distal and proximal ends of the foot. The medial / lateral stiffness is a same except the material is loaded on the medial and lateral sides of the foot. This tendency to respond differently to loads depending on the direction they are applied, along with its breathability, robustness, and relative water resistance are the primary qualities that have resulted in leather having such longevity as the primary material used to manufacture shoe.

The characteristics of the material used such as its stiffness in different directions, will change the elastic qualities of the upper and its ability to conform to the foot's shape. Due to the elastic qualities of leather, after a sustained period of use it will tend to undergo permanent deformation and take the shape of the foot. This effect will be markedly less with nylon uppers which will continue to return to its original shape [74].

Over shorter periods different materials will also respond differently. Taffeta has similar compliance along both its length and breath, whilst leathers will give elastically differently depending on the part of the animal used [74] and the orientation the grain is placed on the shoe. Whilst, nylon meshes will expand in a manner dependent upon the angle in which it is pulled [74].

Simply stating that the upper material is leather may also not be sufficient because the fibre texture varies greatly from being loose in the belly and flank areas of the animal to being relatively tight across the backbone. This results in the leather from over the backbone being six times the strength of that from the belly [74]. Due to these variations in the leather, knowing where the leather is from, its properties in different directions, and ensuring consistency in the use of the materials is important in order to ensure the same footwear has been investigated in each experimental condition. However whilst there are general consensuses within the footwear industry on the effects of material stiffness the full effects have not been investigated by the scientific community. The result of this is that little attention is paid to the materials used in shoe investigations.

It is clear that changing the design of an upper can potentially and quite likely alter the volume inside the shoe available to the foot. If the volume is too large the shoe upper will fail in its role of grasping the foot to prevent slippage and thus the foot may adapt to compensate for this. A compensatory effect to upper design has been witnessed in the case of flip-flops where the toes grip the shoe and gait is adapted to try and keep the shoe on the foot [73]. Alternatively, the shoe volume can be too little as a result the foot will become compressed which has been found to alter pressure [79] and potentially lead to health concerns [89]. The issue becomes further complex when the dynamic shape of foot is considered. Throughout gait the foot shape is continuously changing and thus so is its volume. It therefore seems logical that the ideal shoe would change volume with the foot. To do this the foot must able to contort the upper with minimal effort, however, if the upper contorts too easily it will fail to grasp the foot. It then seems logical that there exists for each last an optimal material and for any given material there is an optimal last volume. Furthermore, we do not know if this optimal volume-material relationship is consistent for all shoe designs or if it changes when the design is altered.

Toe allowance:

This is the amount of material added to the distal end of the shoe (Figure 24), to allow for both variations in people's foot size, and the natural change in foot length experience between days and during gait. Extra toe allowance is often provided if the design of the shoe includes a narrow toe box, since much of the narrowest section has too small a volume for the foot to fit. The design of the shoe will often be focused around the length of the toe box along with the medial and lateral forefoot angles.

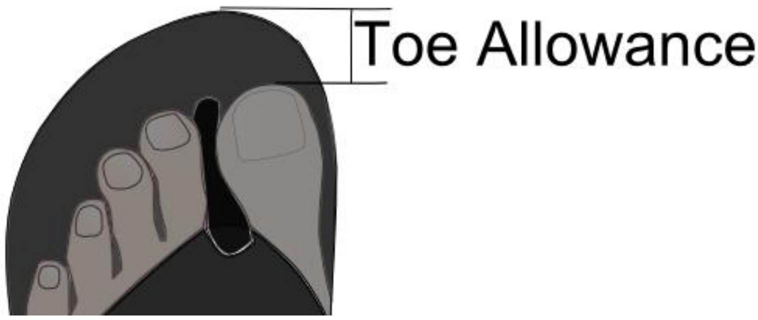

Figure 24: Toe allowance of a shoe

2.3.4. Summary of last and shoe anatomy:

There are a very large number of features of footwear that can be defined and many are interdependent with each other. Furthermore, many of these features have the potential to affect the behaviour of the foot inside the shoe and the loads experienced by the foot, including on the plantar surface. As with heel height (section 1.1) there are clear technical definitions that relate to the last or shoe anatomy. For many of the features defined the definitions do not relate to how the features affect foot anatomy or foot position.

Many of the important features of lasts and footwear that relate to heeled shoes are not defined in in the methodologies of prior literature and there appears to be consistent failure to maintain strict control over important design features of the shoes being investigated. This means that often the shoe being investigated is not fully defined and understood and therefore interpretation of results is difficult and one's ability to compare results across studies is inhibited.

2.3. Effects of high heeled shoes

It has been identified that as many as 37% of women wear high heeled shoes to work [2]. In the same study the participants were asked if their work shoes were comfortable, of those that answered 'no', 62% wore heels. It has also been quoted that as many as 69% of women wear high heeled shoes on a daily basis [69]. Regular wearers of high heels can expect a wide range of effects on their lower limb and gait.

Effects of regular high heel use on bones and joints

Bonney and Macnab [90] highlighted that as many as 90% of the hallux rigidus and hallux valgus operations are carried out on women, the primary users of high heeled footwear. Snow, Williams and Holmes [44] postulated that this may be due to the relatively high number of women wearing high heeled shoes. To advance current understanding of the potential damaging effects of high heels they tested 45 females (22-55 years) who had worn high heeled shoes for at least 4 hours a day for 3 days a week on a regular basis. The tests consisted of plantar pressure measurements whilst wearing shoes with a heel of 1.91 (low), 5.08, and 8.26 (high)cm. They found that when wearing high heels there were higher plantar pressures (Figure 25), less variability of pressure distribution, and a greater loading rate (Figure 26) compared with low heels. There are multiple reports demonstrating that as heel height increases, pressure under the hallux increases [10, 11, 91-93], with as much as a 40% increase in peak pressure at the medial forefoot in high heels (mean, 6 cm heel) compared to low heels (mean, 1.7 cm). This increase in pressure is accompanied by greater loading rates and less variability in the plantar pressure distribution when wearing high heels [44]. These three characteristics combined have been credited for increasing damaging stresses to the bones in the foot and ankle [44].

Area	Barefoot	Low	Medium	High
Hallux	361.48 ± 116.92 a, v, x, y	442.31 ± 127.18 a, z	493.05 ± 147.96 b, c, v, x, y	500.12 ± 144.61 b, c, y
Met 1	235.72 ± 86.29 a, u, w	332.25 ±107.80 a, u, y	432.14 ± 170.89 a, u	480.75 ± 169.20 a
Met 2	345.24 ± 121.78 d, e, v, x, y	340.56 ± 125.05 d, e, u, y	434.98 ± 145.28 a, y	489.62 ± 150.71 a
Met 3	269.19 ± 83.09 d, e, u, w, y	295.64 ± 129.64 d, e, u, y	392.33 ± 120.814 a, u	459.23 ± 140.26 a
Met 4/5	186.00 ± 61.61 a, u, w, x	226.29 ± 100.84 a, z	258.00 ± 131.40 a, u, w	421.37 ± 149.53 a, u

a - significantly different from all other conditions for the given foot area (P<0.003).
b - Significantly different from the barefoot condition for the given foot area (P< 0.003).
c- Significantly different from the low condition for the given foot area (p<0.003).
d - Significantly different from the medium condition for the given foot area (p<0.003).
e - Significantly different from the high condition for the given foot area (p<0.003).
u - Significantly different from the hallux for the given heel condition (p<0.003).
v - Significantly different from the Met 1 for the given heel condition (p<0.003).
w - Significantly different from the Met 2 for the given heel condition (p<0.003).
x - Significantly different from the Met 3 for the given heel condition (p<0.003).
y - Significantly different from the Met 4/5 for the given heel condition (p<0.003).
z - Significantly different from all other areas of the foot for the given heel condition (p<0.003).

Figure 25: The mean maximum pressure for each forefoot area and heel height.
(figure taken from Snow et al [44])

Area	Barefoot	Low	Medium	High
Hallux	2.11 ± 0.95 a, z	2.72 ± 1.23 b, e, z	3.06 ± 1.25 b, z	3.19 ± 1.31 b, c, z
Met 1	1.17 ± 0.74 d, e, u, w, y	1.46 ± 0.73 d, e, u, y	2.02 ± 0.96 b, c, u, x, y	2.10 ± 0.98 b, c, u, y
Met 2	1.73 ± 0.93 e, z	1.51 ± 0.72 d, e, u ,y	1.94 ± 0.88 c, u , y	2.17 ± 1.10 a, b, u, y
Met 3	1.22 ± 0.55 e, u, w, y	1.16 ± 0.63 d, e, u, y	1.51 ± 0.84 c, u, v, y	1.82 ± 1.06 b, c, u, y
Met 4/5	0.69 ± 0.35 e, z	0.55 ± 0.40 e, z	0.75 ± 0.61 e, z	1.21 ± 0.74 a, z

Figure 26: The mean rate of loading during the second half of support of the gait cycle. The values provided are for each forefoot area and heel height. (figure taken from Snow et al [44], the key to abbreviations can be seen in Figure 25)

Effects of regular use of high heels on muscle and tendons

Csapo, Maganaris, Seynnes, and Narici [6] reported that persistent users of high heeled shoes have shortened gastrocnemius medialis fascicle length. To achieve this result they measured a range of muscle and tendon characteristics (Gastrocnemius medialis fascicle length, pennation angle and physiological cross-sectional area , the Achilles' tendon length, cross-sectional area and mechanical properties, and the plantarflexion torque–angle and torque–velocity relationships) in 11 women (age 42.9±11.0 years; height 166.5±7.1 cm; mass 65.6± 11.0 kg) who self-reported use of stiletto high heeled shoes (heel height of 5 cm or over) five times a week for a minimum of 2 years and compared them to a control group of 9 (age, height and mass matched) women, gastrocnemius medialis fascicle length was reduced (49.6±5.7 mm vs 56.0± 7.7 mm). Furthermore, due to a reduced achilles' tendon cross sectional area, the achilles' tendon was stiffer in the high heel group (136.2±26.5 N mm^{-1} vs 111.3±20.2 N mm^{-1}) and these two changes reduce the ankle active range of motion. They suggested this was an adaptation to normalise the sarcomere operating range and take up the tendon slack generated by the change in the ankle joint position. Others have completed similar studies and found that long-term high heel used leads to increased muscle fascicle strains and muscle activation during stance [8]. Together these results suggest that persistent high heel use may compromise muscle efficiency and increase the risk of muscle or tendon strain injuries.

Research has been carried out to investigate the effect of high heels on the risk and mechanisms related to lateral ankle sprains. Foster et al 2012 [7] tested the influence of heel height on frontal plane rearfoot kinematics, kinetics and electromyography of leg muscles during walking. The tests were carried out on 18 healthy females (25.3±4 years, 1.6 ± 0.1 m, and 58.3 ± 8.9 kg) with a high heel of 9.5 cm and low heel of 1.3 cm. They found that wearing high heels produced significantly greater plantarflexion (28.3 degrees versus 9.2 degrees) and inversion angles (9.1 degrees versus 3.1 degrees). Furthermore, the peak inversion moment (0.1 Nm/kg•bwt versus -0.1 Nm/kg•bwt) and the peroneus longus muscle activation (33.2% maximum voluntary isometric contraction (MVIC) versus 15.9% MVIC) were significantly higher in high heels. The plantarflexed and inverted position of the foot when in a high heel may increase the risk of lateral ankle sprains. Finally, there is also evidence to suggest increased shock wave from heel strike and metatarsal strike [14], which may lead to subchondral bone microfractures, could perhaps lead to articular cartilage degeneration and osteoarthritis [15].

2.3.1. *Effects on Trunk and hip*

Inexperienced wearers of high heels show an increase in trunk lordosis as well as pelvic and limb rotation when walking in high heeled shoes [55, 69]. When compared to older adults, younger participants have been observed to have increased lordosis of the trunk at heel strike when wearing high heels (1.7°, SD= 0.8° versus -3.7° SD = 4.7°) [55]. The same study discovered that younger participants, compared to older individuals (average ages of 26.3 versus 43.7 years) had increased anterior tilt of the pelvis at heel strike (1.2° versus -1.3), decreased pelvis range of motion in the sagittal plane (1.7° versus 0.1°). Furthermore the younger participants tended to lean their upper trunk backwards at heel strike whilst the older participants leaned forward (-0.5° versus 2.5°) [55]. These results show that despite both groups being experienced at wearing high heels they have different strategies to overcome the same challenge, thus showing that the response to high heel use is affected by age.

It has also been reported that for each 1 cm increase in heel height there is a one degree reduction in the trunk flexion angle [37]. This was found to correspond closely with changes in the EMG of the erector spinae, which more than doubled when a heel height was increased from 0 to 8 cm [37]. Changes seen in the trunk were not the same for all participants, since external rotation of the trunk at heel strike is decreased in experienced wearers compared to inexperienced wearers [55]. This suggests long term upper body changes can occur with habitual use. Despite this it is apparent that increased heel height reduces hip flexion during swing phase [54, 55, 69] whilst both hip flexion and extension moments are increased during early stance [69, 94, 95].

2.3.2. Effects on the knee

One of the most commonly observed effects of wearing high heeled shoes is an increase in knee flexion at heel strike and early stance [27, 51, 69, 96]. Ebbeling et al [27] tested four heel heights (1.25, 3.81, 5.08 and 7.62 cm) and reported a difference in maximum knee flexion, increasing from 21.1°(6.0) for the lowest heel to 24.9° (7.1) for the highest heel. An increase in knee flexion during stance was also observed by Stefanyshyn who reported an increase in the peak rectus femoris EMG muscle activity (from approximately 0.1 to 0.2 mV) when heel height was increased from 3.7 to 8.5 cm [51]. This study also revealed that with the same changes in heel height there is an increase in knee extensor moment from approximately 30 Nm to 45 Nm, as shown in Figure 27. From these findings Ebbeling et al [27] concluded that the change in centre of mass (COM), observed when wearing high heels, should increase the load on the forefoot. The body must attenuate this increased load which is normally achieved via eccentric contraction of the ankle dorsiflexors during ankle plantar flexion. This is accompanied by eccentric contractions of the knee extensors during knee flexion and eccentric contraction of the invertors during calcaneal eversion [27]. Ebbeling, postulated that in very high heels the ankle is never positioned in the dorsiflexed position and therefore the dorsiflexors are only able to act eccentrically in a much reduced range, preventing them from attenuating the forefoot loads to the same degree. Since the ankle dorsiflexors are no longer able to alleviate shock, this task is delegated to the knee which it achieves via increased flexion [27].

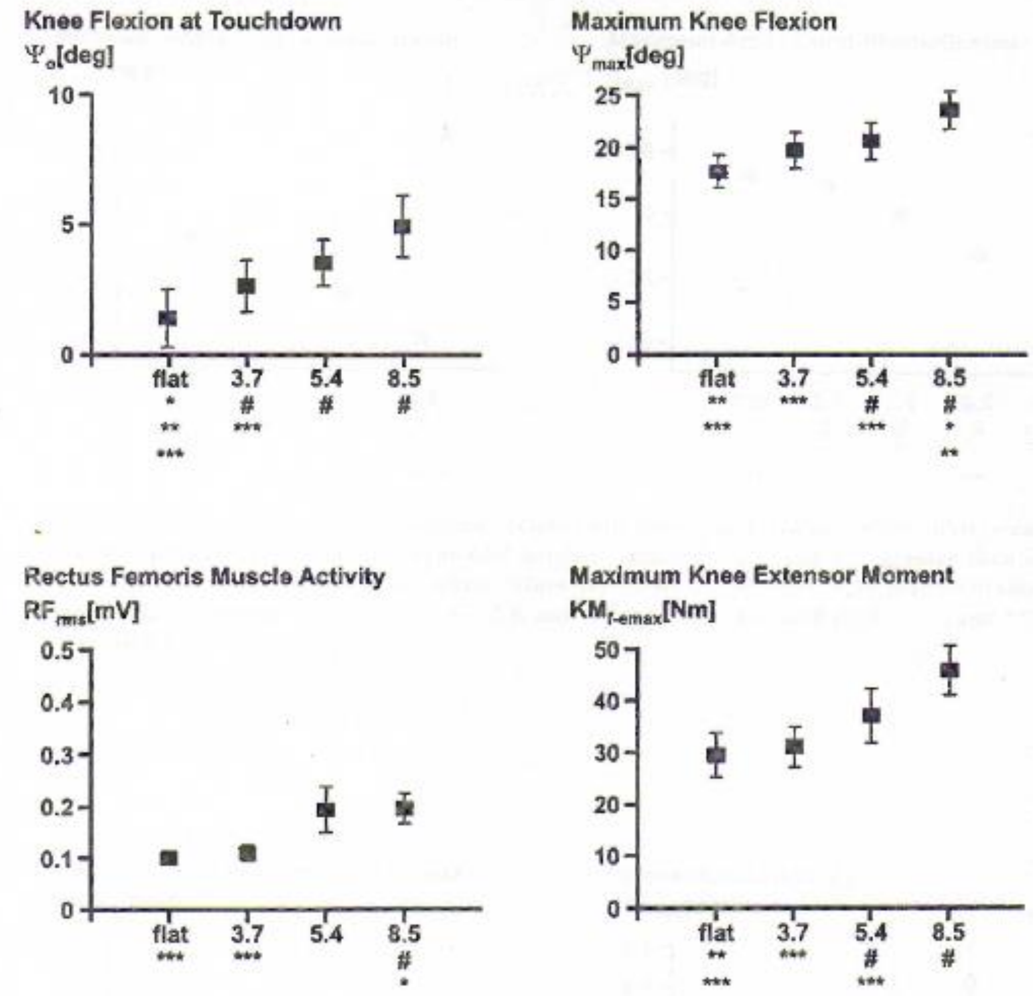

Figure 4 — Comparison of the variables associated with flexion-extension of the knee. Muscle activation of the rectus femoris muscle and maximum knee extensor moment (mean and standard error) for the different heel heights. Positive values for Ψ_O and Ψ_{max} correspond to knee flexion. Significant differences from the flat, 3.7, 5.4, and 8.5 shoes are indicated by #, *, **, and *, respectively.**

Figure 27: The effects of heel height on the knee
(taken from [51])

The compensatory effects seen at the knee to overcome the changed ankle behaviour are continued into the swing phase. During the swing phase, there is a reduced flexion angle of the knee [43, 54, 57, 64, 94]. It has been reported that those walking in low heels have a knee flexion angle during swing of 72.1° whilst those wearing high heels have a knee flexion angle of 66.1°. This is believed to be a compensatory measure for the reduction of torque at the ankle [94]. The increased flexion angle in early stance and the associated increased muscle activity help explain the increase in sagittal knee flexor torque in early stance, which continues into midstance. This also supports the reduced knee torque in late stance [94]. Similarly, the peak knee adduction moment increases when wearing high heeled shoes [54, 64, 69, 94], which is likely due to the increased vertical ground reaction force generating an increase in the magnitude of the early stance knee varus and extensor moments [69].

2.3.3. Effects on foot joint kinematics and kinetics

A well-documented effect of high heeled shoes on the foot is reduced maximum ankle dorsiflexion and reduced maximum ankle plantar flexion with increased heel height [27, 43, 51]. Whilst investigating with participants wearing heels of 1.91 cm (low), 3.81(medium), and 7.62 cm(high) Snow & Williams reported that the maximum dorsiflexion ankle angle was reduced when the heel height was increased, with values of 97.3° (3.1), 91.0° (2.9), 82.3° (2.3) for the low, medium and high shoes respectively [43]. This is in agreement with Ebbeling et al who also used shoes of 3.81 and 7.62 cm (as well as other sizes) and reported a reduction in the maximum dorsiflexion angle between the two shoes of 13.9° [27], similar to the 8.7° change seen in the Snow & Williams [43]. The same two studies reported reductions in maximum plantarflexion of 11.3° (Snow & Willinams) and 13° (Ebbeling et al) between the shoes of 3.81 and 7.62 cm heel height. A similar effect was also reported by Stefanyshn et al, however, this group did not use the same heel heights or provide exact kinematic values. Nevertheless they did provide graphs that provide a good visual evidence of the effects (Figure 28).

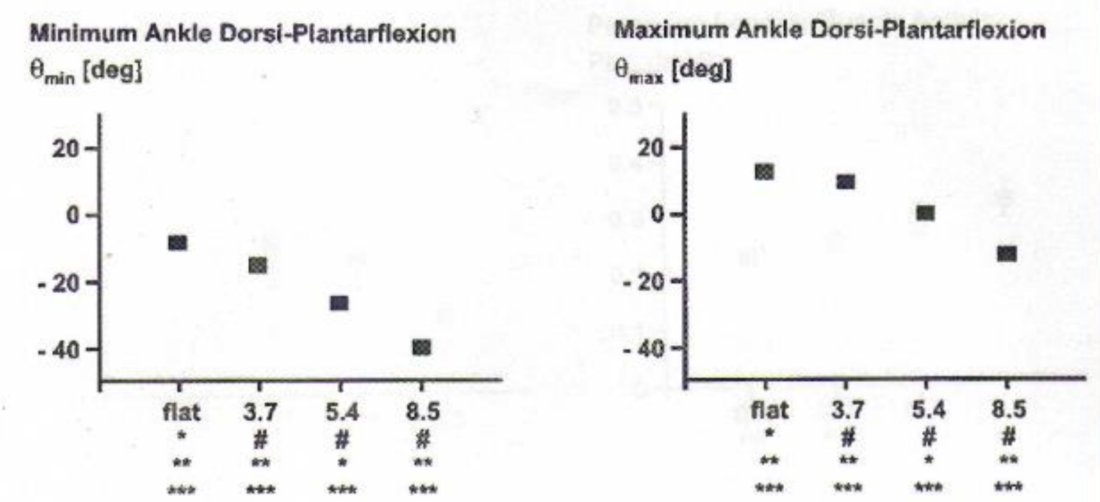

Figure 5 — Comparison of the variables associated with dorsi-plantarflexion of the ankle (mean and standard error) for the different heel heights. Values for θ_{min} and θ_{max} greater than 0° correspond to ankle dorsiflexion, while values less than 0° correspond to plantarflexion. Significant differences from the flat, 3.7, 5.4, and 8.5 shoes are indicated by #, *, **, and ***, respectively.

Figure 28: The effects of heel height on the ankle
(taken from Stefanyshyn et al. [51])

When heel height is increased ankle plantar flexion increases [51] (Figure 28), despite a reduction in ankle plantarflexion moments and an increase EMG activity of the soleus and perneus longus [51]. It has been suggested that, as the ankle plantar flexion position is increased in late stance, the moment arm length of the Achilles tendon is reduced. As a result, the same contractile activity of the posterior calf muscles results in comparatively less plantar flexion moment and thus greater contractile activity is required to produce the necessary moments [51].

With increased heel height the medial arch of the foot is increased in height [67]. Whilst a number of papers reported this, the only study to quantify this effect was Shimizu and Andrew, (Figure 29) [97]. Lifting the heel above the forefoot forces the toes into extension, an assumed precursor to the windlass effect [31] which increases medial arch height as well as foot supination [31]. If tension in the plantar fascia and the other plantar structures is the reason for an increase in the height of the arch of the foot, then other effects of the windlass effect might be expected [98, 99]. These include a reduction in foot length (a reduction in arch lengths has been observed [68]), and perhaps greater compression loads at joint surfaces as tension in the plantar structures increases. This increased tension in the plantar structures will stiffen the foot making its structure more rigid, a stiffer structure has reduced absorption capability and thus the damping capabilities of the foot are reduced, as well as its the ability to adapt to changes in the supporting surface [30].

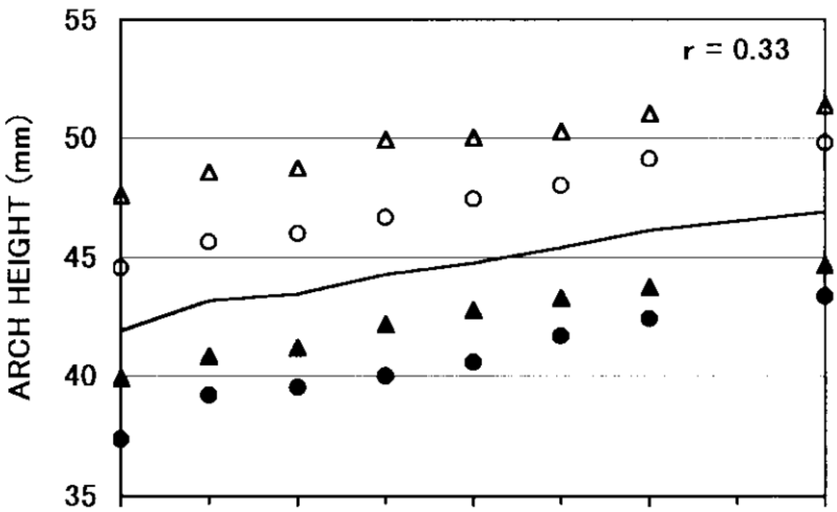

Figure 29: The effect of heel height on longitudinal arch height [97]
with heel heights of 0, 5, 10, 15, 20, 25, 39, and 40 mm.
Filled shapes represent low arched subjects, empty shapes represent high arched subjects, triangles represent subjects with weak rearfoot pronation, circles represent subjects with strong rearfoot pronation, and the line shows the overall mean values.

2.3.4. *Effect of high heeled shoes on loads applied to the foot*

The literature reviewed thus far reports the effects high heels have on the joints of the lower extremities. At each joint there are two primary changes, the angle of the joint is altered and the loading of the joint changed. Whilst some of the loading is the result of changes in muscle activation much more is a result of the loading due to body weight and the corresponding ground reaction force. Therefore, understanding how the loading of the foot changes when high heels are donned is imperative in order to understand how the joints of the body are loaded. The key measure for this is plantar pressure since this illustrates how the primary loads applied to the foot are distributed under the foot during gait. The relationship between heel height and plantar pressure is therefore a key part of the understanding of the effects of wearing high heeled shoes. However, whilst studies have shown that heel height has an effect on EMG [100], heart rate and oxygen consumption [27] are non-linear, investigations into the effects of heel height on plantar pressure have never systematically changed height and reported corresponding changes in plantar pressure. Instead researchers have studied shoes that are readily available to them. The effect of this is the differences in height between the shoes are arbitrary except for the fact that one is higher than the other. As such, we do not know at what height the plantar pressure significantly increases.

The two figures (Figure 30 & Figure 31) provide a simplified model of how forces act on the plantar surface of the foot in two different shoe designs. As previously explained by Broch et al [101], in the first (the flat shoe), forces acting on the plantar surface are located primarily under the forefoot and the heel. (F) The force under the forefoot has a moment arm of (f) between the centre of force application and the line of action around the ankle centre (where line A intersects it). The force under the heel (H) has a similar moment arm (h). The forces that act upon the heel and forefoot must create an equal moment at A in order to maintain stable standing and no rotation of the ankle.

Figure 31 illustrates the effect of elevating the heel above the forefoot, as occurs when wearing a high heeled shoe. The changed foot position results in a reduced moment arm f and an increase of moment arm h. However, there still needs to be equilibrium of moments acting on A, in order to maintain balance. Therefore there is a reduction in force H and an increase in force F.

When wearing high heels the foot is plantarflexed, which reduces its functional length and makes the foot a more rigid structure. This has the net effect of the forefoot carrying more load, and the heel less than during normal walking. Despite the lack of systematic study of heel height and changes in plantar pressure, this effect has been repeatedly observed in the literature. Several studies confirm the general observation that there is an increase in the pressure at the forefoot [23, 39, 44] and a reduction in pressure under the heel when heel height is increased [23, 25]. Furthermore, the increased pressure on the forefoot is focused on the medial side, with a reduction in pressure observed on the lateral side [23, 25, 39, 42, 53, 65]. The vertical and anteroposterior ground reaction forces also increase [25, 27, 43, 51], there is an increased impact force [42], reduced time to maximum pressure [44], and higher force-time and pressure-time integrals at the medial forefoot [23].

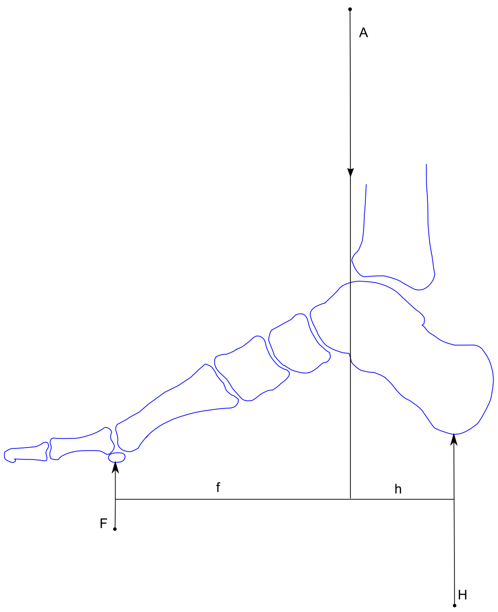

Figure 30: An unshod foot or foot in a neutral heel shoe during quiet standing
(adapted image from Broch., et. al)

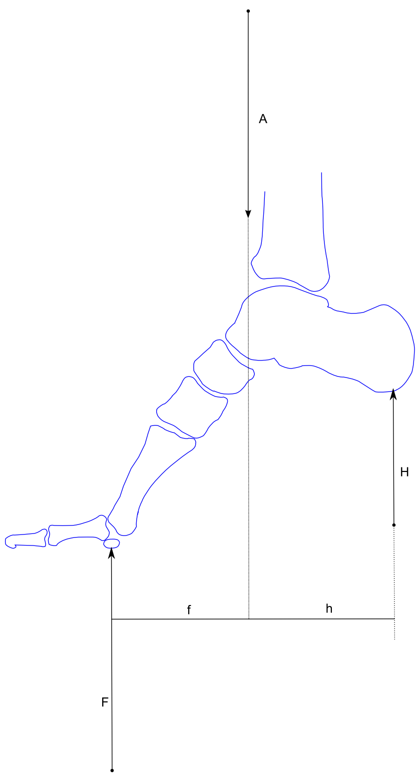

Figure 31: A foot wearing a raised heel shoe during quiet standing
(adapted image from Broch., et. al)

Understanding the effects of different footwear designs on gait can enable their appropriate use, since a design might place one person at risk but offer therapeutic benefit to another. It is clear from past research that an increase in heel height results in an increase in forefoot loading when standing [43] particularly on the medial side of the foot. As a result the force experienced at the first metatarsal phalangeal joint (MPJ) when wearing high heels has been reported to be twice that when barefoot [23, 39]. However, shoe inserts under the forefoot change the material properties in contact with the foot and can alter the 'fit' of the shoe, and have been shown to reduce pressure and increase comfort [102, 103]. This suggests that plantar pressure and comfort are related to shoe fit (the matching of the foot and shoe shape, which is explained in much greater detail in chapter 5) in high heeled shoes [42].

Other health related effects of high heel use

Most shoes are designed primarily for fashion but some shoes are designed specifically to help prevent health issues or to protect feet. To protect the foot in the work place some industries require the employees to wear metal toe capped shoes, which will make the shoe very stiff and humid, promoting new foot problems [89]. Despite creating problems for foot health the metal toe cap is still required to reduce risk of significant traumatic injury. Conversely, shoes designed for those with diabetes will be made with a soft very wide fitting upper to reduce the risk of ulceration due to loads from the upper.

Many people and professional organisations (e.g. Society of Podiatrists and Chiropodists) generally consider high heeled shoes to be ill-designed and poor fitting. If these designs lead to increase plantar pressure, as is often proposed [23, 25, 34, 39, 42, 44], then this 'damning' of heel height may be valid given that increased plantar pressure has been associated with clinical problems for diabetes sufferers and conditions such as metatarslagia [104]. Indeed, studies have refered to metatarslagia as a symptom of wearing high heels [104, 105] although it is in fact a generic term for pain in the metatarsal region (assumed to be due to excessive plantar loading). This can occur due to a number of conditions, including: inflammation of the metatarsal heads due to overuse, increased stress on the foot from high heels or the individual being overweight, Morton's neuroma, hammer toe or claw deformity, hallux valgus, stress fracture of the metatarsal, arthritis, gout, or diabetes. One theory relating to a specific cause of metatarsalgia is that the thickening of the nerve tissue is the result of compression of the nerve in the inter-metatarsal space (Morton Neuroma) [80]. This compression is thought to be due to too narrow toe boxes. This assumes the upper material stiffness is able to provide a reaction force sufficient to prevent the forefoot widening as it is loaded, thus compressing the tissues in between the metatarsals. Increased forefoot plantar pressure may worsen the condition [4] as greater load passes through all the forefoot tissues. This example illustrates the importance of understanding how design features commonly used with high heels, such as narrow forefoot area and stiff uppers, might further contribute to changes in plantar pressure and the associated foot problems. Stress fractures are often a result of high repetitive loading of a bone and some have suggested habitual high heel use increases fracture risk [80, 105]. However, there is currently no data profiling the causes of metatarsal stress fractures to substantiate this.

The effect of high heels on comfort

Studies have demonstrated that high heel shoes are a risk factor for increased plantar pressure under the forefoot associated with increased risk of poor foot health and reduced footwear 'comfort' [9-11]. Indeed, an increase in plantar pressure of 15kPa has been shown to reduce comfort rating by 0.6 points on a 5 point rating scale [106]. However, by contrast, high heel shoes have also been used as a therapeutic technique for symptoms such as plantar fasciitis, as well as tendinitis and partial ruptures of the Achilles tendon [101]. Even relatively small changes in the forefoot dimensions of the high heeled shoe can affect comfort. It has been shown that women with a wider foot are more susceptible to foot pain. de Castro 2010 reported that women without foot pain had a forefoot circumference equivalent to 98.27 (±4.42)% of foot length, whilst those with foot pain had a larger relative circumference, 99.39(±5.55)% of foot length (p =0.048) [107]. Thus it seems that poorly fitting footwear can cause mechanical stresses that are detrimental to foot health [108].

Questionnaires assessing the comfort of high heeled shoes have so far shown that discomfort increases with heel height [109] and the design of the shoe plantar surface (footbed) can be optimised for comfort [66]. In particular the heel wedge angle and heel seat length play an important part in the perceived comfort [110]. It has been shown that mediolateral ground reaction force is increased as a function of heel height

[27] and it has also been identified that stability is an important factor in the rating of a high heeled shoe's comfort [111].

2.3.5. Summary: The effects of wearing high heeled shoes.

A high heel shoe is a female dress shoe that raises the heel of the foot. Shoes of this genus are often regarded as the originator of foot, and lower limb, health problems. Many researchers attribute the high pressures observed under the forefoot, as well as the constriction of the toes and the metatarsal phalangeal joints within narrow toe boxes, as the primary causes of numerous foot health problems. Despite this, some features such as increased heel seat length have been shown to reduce the pressure under the medial forefoot, it is therefore apparent that by changing features other than the heel height, it may enable shoes of this type to be less damaging to the wearers foot health. Thus, some changes in footwear design might counteract the negative effects of other changes.

High heels affect foot position, load distribution under the foot, knee and hip flexion, and trunk movements, and habitual use leads to structural changes in muscles and tendons. However, in no case has the effect of heel height on total plantar pressure or plantar pressure distribution, whilst either quiet standing or during gait, been investigated as heel height is systematically increased and made the independent variable under investigation. Thus, there is no definition of the precise measured effects of increasing a measured heel height on plantar pressure. Therefore, defining what constitutes a high heel is difficult, and outlining to consumers how a shoe of a given heel height may affect their health is not possible. It is equally clear that changes in heel height rarely occur in isolation, and that there are specific footwear features associated with high heeled shoes that might also contribute to change in foot biomechanics. The interactions between footwear design features of high heeled shoes and their respective effects on important biomechanical parameters such as plantar pressure have not yet been adequately independently studied.

2.4. Gaps in the current knowledge of high heeled shoe design.

2.4.1. Shoe volume

The shoe volume is the amount of space the internal structure of the shoe provides for the foot. Whilst, as explained above, the design of the shoe will affect the internal volume, it can also be changed in two principle ways that provide the customer with a choice. The first method is to change the length of the shoe which is measured in shoe size (e.g. UK 9 or mondopoint 270). The second method is to change the width which is usually measured on a Brannock device and recorded as a letter A-EE, each a quarter of an inch larger than the previous. However, it is often more accurate not to consider the width of the shoe but instead the circumference of the forefoot at its widest point, a measurement equivalent to the ball girth of the last [74].

Shoes are only sold with two variables (length and width) despite the fact that the a last maker will use six measurements to define their lasts (ball girth, waist girth, instep girth, long heel girth, short heel girth, and overall heel-to-toe measurement of the last called stick length) [74]. Due to the many contours of the last there are many more degrees of freedom than these six measurements can constrain. As a result, the final shape of the last still has an infinite range of possible shapes, which may affect the total volume. The difficulties in controlling the volume may be the reason that shoes of the same size but made by different companies often have sundry dimensions. With examples being shown where there are three-eighths of an inch difference in overall length, which is greater than a full size [74] .

Incorrectly sized shoes do also have associated health risks including ankle pain [112]; toes, metatarsophalangeal joints, sole of the foot and heel pain [113]; increased plantar pressure associated with ill-fitting shoes has been shown to increased plantar ulceration [114]; this increased pressure at the forefoot can lead to increases in pressure in the intermetatarsal space which in turn can lead to or exacerbate the symptoms of patients fat pad atrophy, Morton’s neuroma, and metatarsalgia [80].

A shoe is designed to be aesthetically pleasing, it therefore has smooth contours, in contrast the foot is an irregular shape, footwear fit therefore involves the matching of an irregular shaped foot with the regular shaped last [115].The shoe will need to be sold to many people and all feet are different, even the two feet of the same person are a different shape [74] and they continually change shape dependent on activity [116]. After an hour of barefoot standing a foot will increase in volume by 5% due to edema [74]. The shoe will also change shape increasing in length, width, and volume after prolonged use, a characteristic that is more prominent with leather uppers than those that are made from nylon [74]. A shoe designer therefore has the difficult task of designing standardised and often mass produced product with smooth contours for an irregular, inconsistent foot. Whilst this may already seem impossible the designer has to do this with a material that changes shape for an ever evolving foot.

The designer's task is worsened by the wearer's apparent inability to either recognise a good fit or their wiliness to wear shoes that are ill fitting. Whilst the wearer is able to distinguish change in widths and circumference in the toe and forefoot regions [117], a shoe that is lose fitting is generally considered more comfortable despite its function possibly being impaired [118]. For example it has been shown that loading rates and pronation velocities in the tightest and highest lacing conditions are reduced [119]. It has also been recommended that for the best fit the shoe should be in fact narrower than the foot [120] and for proper fit a shoe should be no more than 6.25mm narrower than the foot. Despite the recommendations, shoes have been reported as narrower than the foot by 10.22mm (running shoes) [121] and 7.27mm (outdoor footwear) [122]. The correct fit would then, depend on the stretch (stiffness/elastic) properties of the upper and the cushioning properties of the midsole [115]. It is therefore apparent that in order to produce a correctly fitting shoe, to aid comfort and promote a healthy foot. The shoe designer has an inherently difficult task, thus investigations that highlight good practice or identify the worst scenarios will provide useful tools for the improvement of footwear.

2.4.2. Shoe upper volume and plantar pressure.

Footwear fit has been defined as the functional geometrical match of the foot to the shoe [123]. This issue is so difficult to quantify that despite studies showing its importance to the consumer it has been stated that *“big companies have no interest in such difficult ventures”* [38] (in reference to global sports brands such as Adidas and Nike). Despite this, fit is still an essential requirement of footwear with 70% of people that are interested in customised shoes stating that “improved personalised fit” is the primary rationale [38]. Goonetilleke, provided an incomplete list of criteria which determine and influence fit, which included: last and foot anatomical shape, construction and material selection of the shoe, shoe pattern design, climate, season, daytime [it is assumed the author meant the time of day when the shoe is worn], the body’s biological cycle and psychological perception [38]. Even from this brief list it is clear there are many complexities to defining and measuring footwear fit. Poor fit has been identified as one of the primary reasons for many foot conditions [79] and therefore the difficult task of improving fit remains important. However, systematic investigation of some of the major factors influencing “fit” is required first so as to provide guidance to design changes that might improve fit. The appropriateness of the basic geometric relationship between foot size and shape and shoe volume and shape seems critical to footwear fit.

The feature of the shoe upper frequently blamed for poor fit is, a narrow and shallow toe box that compresses the forefoot, a characteristic that could increase forefoot plantar pressure [10]. Also, a 4mm reduction in medial forefoot fit (difference between the foot and last dimensions) will result in a 4 point reduction in comfort (on a 7 point fit rating scale) [118]. However, when shoe laces are tightened, reducing the internal volume of the shoes and increasing the tensile force in the upper, plantar pressures are reported to reduce under the lateral midfoot by 24.8%, but not elsewhere under the foot[124].

Whilst studies have suggested that the fit of a shoe is improved when the shape of the shoe closely matches that of the foot [125] there is a lack of scientific evidence for this [126]. Investigations have demonstrated that the quality of fit is highly subjective, complex and dependent upon past experience [127]. For example, those with wider feet have been found to suffer with more foot ailments [79], yet they are also more likely to prefer a tighter fitting shoe [127]. Even if a shoe was designed for a particular person undertaking a particular activity there are still discrepancies between the two feet of the same individual [74]. Despite this, studies have shown some success of adapting fit and as a result there are some features of the shoe for which we know how to improve fit. For example the heel fit affects the eversion of the calcaneous [128] and a tighter and higher fit from lacing will result in reduced loading rates and pronation velocities [124].

High heeled shoes require the upper to hold the foot in position despite body weight and gravity attempting to make the foot slide forward. If the foot is able to slide forward the toes will become crushed in the toe box and cramping of the toes in the toe box has been associated with foot deformities and discomfort [79]. The volume of the upper and its geometry need to be a close match to the foot shape to hold the foot in position and thus have “good fit”. However, if the shoe is too tight it will become uncomfortable and a health risk. To improve comfort a softer material may be used, however a softer material may fail to constrain the foot sufficiently and no longer hold the foot in place inside the shoe. There is therefore a need to understand the relationship between the volume of a high heeled shoe, how this volume may change when different materials are used, and the behaviour of the foot inside the shoe (e.g. the loads experienced on the plantar surface).

The fit of the upper may not be solely due to the upper itself. After extended periods of standing the foot may increase in volume [74]. Whilst, the material used in the insole of the shoe may also have an effect. A highly compressible material may provide more room once it is compressed under body weight. Also, some materials may become permanently compressed after repeated loading cycles over successive days or weeks, and thus fit is a dynamic quantity [115]. There have been many attempts to include insoles in shoes to improve the match between the shape of the plantar foot and the sole of the shoe [116]. Whilst there are reports of benefits to their use, not all insoles are successful. It is unclear if some insoles are unsuccessful because they occupy so much space inside the shoe that the internal volume of the shoe is significantly reduced and thus the insole compresses the foot against the shoe upper. Reducing the available volume in the shoe may result in high compression of the foot as explained in the case of the upper properties (see above), this is due to the deforming foot being constrained as it receives the ground reaction force. Constraint of the forefoot due to the shoe volume could lead to elevated plantar pressures.

Equally, increasing volume might reduce pressure and mitigate the effects of other design features that have elevated plantar pressure.

The material used will have an effect on the temperature and humidity inside the shoe, which may affect the foots response to its environment and the degree of friction between the foot and shoe [115]. Changes in the temperature of the foot will change the blood flow to it [129], edema in the foot, possibly due to increased levels of blood, has been associated with a 5% increase in foot volume [74]. This is not the only reason that the foot will change shape. The foot will also increase in volume after prolonged standing [74] and during walking [130]. As a result the shoe upper is required to perform two almost contradictory tasks: holding the foot it the correct position in the shoe whilst also allowing the foot to undergo rapid and complex changes in its shape. The importance of these requirements will differ for different shoe types, designs, and individuals. For example, a stiff robust outdoor shoe provides more volume for the foot than the more flexible, light weight running shoes [121], an adaptation that is possible because the task it performs is very different. The upper of the high heel shoe has a much more difficult task than many other shoe types with regards to holding the foot in position. If the upper fails in completing this task the foot will slide forward and the toes will be compressed in the toe box. However, there is a clear interaction between the volume of space provided for the foot, the foot shape and the material properties of the upper in this mechanism. It is unclear how much volume the upper should provide for the forefoot to adequately constrain the foot and how this design choice should change when different upper materials are used, or how the effects of material stiffness and shoe volume interact with the effects of heel height on foot behaviour. As a result it is also not clear what the best material and volume combination is, in order to produce effective, comfortable high heeled shoes.

2.4.3. Methods of manipulating shoe volume

Last makers and researchers have now defined many more features of the last than the 6 used by traditional last makers and investigations have identified a number of their effects. Whilst, some last features have a direct effect on the total volume inside the shoe, others may affect the volume that is useable to the foot, a prime example of this is last flare, described in Chapter One. There has been much debate on last flare, if it is a natural feature of the foot or a result of wearing curved shoes from a young age is still unclear [73]. This is perhaps why there is much variation between manufactures with examples having both outflare and inflare [74]. Conclusions have however been drawn on the effects of excessive or insufficient flare. These conclusions have shown that deviations from the neutral position are consequential in the impairment of stability, strength and potentially increased risk of injury [73].

The volume of the forefoot is of particular importance to foot health, with wider fitting shoes having been shown to reduce foot pain [4]. This is of particular importance because two thirds of elderly females are reported to wear shoes with toe boxes that are too narrow [79]. These reduced volumes increase the pressure in the plantar forefoot, which have been shown to subsequently produce larger pressures in the intermetatarsal space and metatarsal heads. These conditions exacerbate the symptoms of patients with fat pad atrophy, nonspecific Metarasalgia and Morton's neuroma [80].

The total volume available can also be reduced by changing the toe box design, in particular changing the medial and/ or lateral forefoot angle (explained earlier in this chapter). These angles are often changed to adapt the toe design from that of a rounded shoe to a pointed toe shoe. Whilst, round toed shoes show the least pressure around the medial aspect of the toes, pointed shoes have been shown to produce the least pressure on the lateral toes [4, 79]. Pointed shoes commonly are narrower than the foot at the forefoot, wearing shoes that are significantly narrower than the foot has been associated with lesser toe deformity [122]. Almost any adaptation to the upper will affect the volume of the shoe which can subsequently affect the loading of the foot. A case highlighted by results showing that loading rates and pronation velocities are reduced in shoes with the tightest and highest lacing [119], a relatively small shoe adaptation.

Insoles have been shown to reduce plantar pressure, attenuate impact force, and improve comfort [116]; reduce the pressure time integral, increase contact area [131]; and reduce injury frequency [132]. However, they also take up space inside the shoe and thus the volume available to the foot, the reason perhaps why adding 'extra' support has been shown to be ineffective [133] and a possible reason for an increased number of blisters when wearing insoles [134]. An opinion strengthened by the fact that blisters, bunions and pain have all been reported as possible results of poor fitting shoes [121].

2.4.4. Shoe upper properties and plantar pressure.

The characteristics of the upper material, such as its stiffness in multiple directions, will change the elastic qualities of the upper and its ability to conform to the foot's shape. These changes will affect the reaction force the upper applies to the foot. Due to the elastic qualities of leather, after a sustained period of use it will tend to undergo permanent deformation and take the shape of the foot. This effect will be markedly less with nylon uppers which will continue to return to the original shape [74]. Over shorter periods different materials will also respond differently. Taffeta has similar compliance along both its length and breath, whilst leathers will expand differently depending on the part of the animal used [74] and the orientation of the leather grain. Nylon meshes will expand in a manor dependent upon the angle in which it is pulled [74], it is therefore clear that both the stiffness and the orientation of the material used in an upper are imperative to fit and thus comfort. Whilst there is a good understanding of shoe material stiffness from mechanical tests, its relationship to plantar pressure and comfort and thereafter foot health is at best theoretical. There is, therefore, a need to better understand the potential changing requirements of the shoe upper as heel height changes, how material stiffness affects plantar pressure and how this effect interacts with heel height.

2.5. Observations on the research protocols used in prior plantar pressure research studies

Increased heel height often results in a reduction in walking speed and a reduction in shoe-ground contact area. This is of particular importance to pressure investigations as both can affect the plantar pressure recorded [135]. Thus both must be considered when investigating the effects of heel height and associated shoe design features on plantar pressure. Studies have used a number of techniques to overcome this. Whilst some allow the participant to walk their own selected speed but keep it consistent between shoe conditions, others have used metronomes [136] or treadmills [137], and many have used a pre-selected walking speeds that all participants must adhere to [114, 138]. Each of these has advantages and disadvantages. The metronome has been used in an attempt to maintain participant walking speed however it does not control speed, but rather controls cadence. Thus the final speed the participant walks will be dependent upon their stride length and speed will vary between participants. It may also be true that the cadence of one participant does not suit that of another and therefore their gait will be affected. Whilst treadmills are ideal for maintaining the speed of a participant there have been studies that show that gait on a treadmill is significantly different to that when walking on flat ground [91].

Allowing the participant to select their own walking speed can create variations in pressure due to the change in walking speed between shoe conditions, which can be made worse if one of the primary effects of a specific shoe is to affect walking speed. Allowing a participant to select their own speed with one shoe may mean that they are unable to adopt that same speed in another shoe subsequently tested, rendering a comparison of the pressure data between the two shoes invalid. A further technique is to ask the participant to walk at a set speed. Limiting their speed in this way may affect the gait of the participant but this should be minimal if the speed chosen is close to the participants preferred speed. This technique may however result in an excessive number of walks being required of participants, since only those of the correct speed will be accepted.

Walking may seem to be a consistent pattern but in fact there is significant variability of up to 66% between individual footsteps [139]. For this reason a number of steps are averaged to provide representative data to describe plantar pressure in an experimental condition. However, the number of steps required will be related to the amount of variation between steps in the data. This variation might be person specific, but also shoe specific because as the literature illustrates, footwear design features can affect foot and gait biomechanics in different ways. One study has identified the number of steps required to provide representative and therefore valid plantar pressure gait data, which reported 12 steps in cases where those with neuropathic diabetes were tested whilst wearing custom made footwear [26]. Neuropathic participants are known to have an adapted gait and diabetic footwear includes a number of design features that separates them from more commonly worn footwear [77]. Therefore this result may not easily transfer to investigations of other shoe designs in other cohorts. Furthermore, when testing different footwear designs a period of acclimatisation is to be expected for each shoe, and most researchers build an acclimatisation period into their protocols. However, this acclimatisation period has never been investigated in order to provide recommendations for the number of steps required to acclimatise to a shoe. Nor is it known whether this acclimatisation varies between different shoes. This is despite numerous studies proving that footwear of varying genera

and ever small changes between similar shoes can have an effect on numerous variables (e.g. muscle activation [100], oxygen consumption [27], comfort and plantar pressure [53]) that may affect the time it takes a person to familiarise them self with a footwear condition.

2.6. Summary of chapter 2

From the literature a number of issues relating to high heels have become apparent. A key role of a shoe is to protect the foot and allow comfortable and risk free ambulation. However, there is a lot of literature that documents a wide range of foot and lower limb conditions that are at least in part, attributed to the use of high heeled shoes. Despite this it is not clear from the literature what constitutes a "high heel". In fact this issue is twofold, not only is there inconsistency in the landmarks on the shoe used to measure the heel height, but there is also a lack of consistency in the literature concerning the height at which one considers a heel to be "high".

The effects of heel height on the body are considerable and investigations have found significant effects on the body from the toes to the lower back. Whilst there are large effects at the hip and knee, the greatest effects of a high heel are at the foot and ankle. As a result a number of foot health concerns at these locations are attributed to the use of high heels. Furthermore, the increased plantar pressure observed when heel height is increased is often regarded as a key catalyst for varied clinical conditions and reduced footwear comfort.

One of the reasons why there is no clear definition of the height at which a heel becomes a health concern is that studies have not controlled heel height in a systematic way, i.e. as an independent variable. Prior studies have therefore been unable to confidently attribute and describe how heel height is related to important parameters such as plantar pressure. This issue is compounded by the fact that there is no consistency across studies in the design of the shoes investigated. This prevents data from several studies being pooled but also means that it is not clear how other design features of the shoes tested, that also varied between experimental conditions, affect plantar pressure, foot motion or any other important characteristic.

As reported above, shoe upper stiffness [89], fit [107], and upper design [79] may all have an effect on plantar pressure which can lead to foot health concerns. Whilst we know by virtue of its stiffness that an upper can inhibit the movement of the foot [89], we do not know at which point an upper can be defined as “too stiff”. Nor do we know if the optimum stiffness for a shoe upper varies as upper fit (geometry) or heel height is altered. In high heeled shoes there is a need for the upper to hold the foot in place and prevent it from sliding forward. Thus a material requires sufficient stiffness to fulfil this task adequately. However, since foot shape, and therefore upper fit, varies at different heel heights, it may be appropriate to investigate the effects of upper stiffness at varied heel heights. If a stiff upper poses a risk to foot skin and elevates plantar pressure by constraining the foot against the sole, designers should either avoid using the upper or its use should be reserved for those heel heights that absolutely require it (and the shoes restricted to occasional use).

To investigate this issue a simple comparison of a high heeled shoe and low heeled shoe, each made with two different upper materials (i.e. 2 x 2 study design) may not be sufficient. Whilst such a research design may identify a difference between each shoe type, it would not establish whether any difference observed occurred systematically as heel height and stiffness was increased. It might be that the effect of either footwear feature is limited up to a specific level (i.e. heel height of 65mm) but important thereafter. A more informative research design would include shoes with a range of heel heights, and at each height upper stiffness could be varied in perhaps 3 increments. Through this approach the wider relationship between a full range of heights and upper stiffness, and any interactions between upper stiffness and heel height, could be characterised. Trends between the effects of two design factors (upper stiffness and heel height) might enable us to identify key heel heights or upper stiffness values where pressure and comfort are significantly changed. This could provide a designer with the important information on how to select material stiffness for any particular heel height. It may also lead a designer to be less concerned about the effect of upper stiffness with shoes of a specific range of height, since those heel heights have no or limited effect on plantar pressures.

Plantar pressure is associated with footwear comfort [119], comfort is synonymous with fit [121] and it follows that plantar pressure has been described as a valid measurement of footwear fit [121]. It is therefore unsurprising that methods that improve fit, such as insoles, have been shown to reduce plantar pressure and improve comfort [9, 109].

A shoe that is loose is rarely considered uncomfortable in spite of its function potentially being impaired [118], and researchers have suggested that loose fit can result in slippage between shoe and foot which ultimately can lead to injury of the soft tissue due to friction [21]. There are a number of possible reasons for the inability to distinguish the shoes fit. Discomfort of footwear is predominantly due to localised pressure induced by unsuitable shoe design [115, 140]. As a result, standing still or during short walking periods the pressure of a loose fitting shoe seems reduced to the wearer. However, during short periods of standing or walking the foot is not subjected to the repetitive loads experienced during gait were the cumulative effect of successive localised loading could have an effect. Another possible reason loose fitting shoes are considered comfortable after short periods may be that participants are not able to discern small differences in pressure, instead they make comfort decisions on contact area, fit of the upper, weight, etc. [141]. As a result research that solely relies on subjective data acquired from the participants during short testing periods may be bias.

Strategies to improve fit include the shoe lacing system [119], toe box shape [79], the elastic properties of the upper material, the cushioning characteristics of the midsole material, and the construction method [115] all of which change the volume inside the shoe and result in a change in the plantar pressure recorded. However, the precise effect of each is yet to be scientifically scrutinised.

Due to both its impact on comfort and foot health it is apparent that there is a need to better understand shoe fit. It has been shown that both volume [116] and material stiffness [115] can affect fit and plantar pressure but there is no investigation into how these two key factors affect each other. We therefore do not know how we should change the dimension of the upper when a material of different stiffness is selected. There is reason to believe that changes to the upper dimensions are required when the material stiffness is changed. For example, in running footwear the shoe has been found to have a breadth (width at widest part) 10.22mm smaller than the foot [121] whilst an outdoor shoe was found to be only 7.27 mm smaller [121]. It has also been shown that at high intensity activity over extended duration the foot increases in volume [74], therefore whilst the running shoe is narrower it is also subjected to the largest expansion of the foot, yet it was still regarded as a good fit. This is likely possible because the materials used for athletic footwear are less stiff than that used in outdoor footwear. There is therefore a need to better understand the relationship between the required volume inside a shoe and shoes material properties, in particular that of the upper.

Finally, before it is possible to investigate how footwear design features affect measures such as plantar pressure, understanding how quickly a person acclimatises to walking in an unaccustomed shoe is critical. An investigation of various high heeled shoes might not capture valid data if insufficient time is provided for the participant to become acclimatised to the shoes. Likewise, understanding how many steps must be recorded in order to provide a valid characterisation of the effect of a shoe on plantar pressures must also be understood. These two methodological issues have not previously been investigated with sufficient rigour and certainly not for retail footwear. The objectives of this thesis are therefore:

1) To produce protocol recommendations for studies that investigate how footwear design features affect plantar pressure. (chapter 3)
2) To investigate the effect of an incremental increase in heel height on plantar pressure and comfort (chapter 4)
3) To investigate the effect of an incremental increase in upper material stiffness on plantar pressure and comfort (chapter 4 & 5)
4) To investigate the effect of an incremental decrease in forefoot shoe volume on plantar pressure and comfort (chapter 5)

Once these objectives have been completed their results will be used to suggest improvements to future research protocols (objective 1), and provide invaluable information to footwear manufactures when designs for comfort or to reduce the risk of injury (objectives 2-4).

Chapter 3: An Investigation into the Number of Steps required to Produce a Valid Representation of Gait and the Number of Steps required to Acclimatise to Unfamiliar Footwear (A Methodological Study)

Chapter 3 Introductory Outline:

The aim of this Chapter is to ensure that the data collected in the remainder of this thesis is of high quality. The methods of past studies were investigated and tabulated in order to aid comparison. The literature search revealed that there were limitations in current methodologies that could be affecting the quality of the results presented. In order to improve future data collection and ensure the quality of data, this chapter designed and carried out an investigation into plantar pressure measurement protocols. In particular the number of steps that a participant should be required to take during data collection was investigated. This number was made up of two subsections: the number of steps required to become acclimatised to unfamiliar footwear, and the number of steps required to produce reliable data.

3.1. Introduction:

To improve footwear for both the health and the comfort of the wearer, a greater understanding of how shoe features affect the foot is required. Of the various measurement techniques available to footwear investigators, in-shoe pressure measurement currently offers the most potential. In-shoe plantar pressure measurement allows us to quantify the effect of a given shoe feature on the major load bearing surfaces of the foot. It, therefore, allows us to identify changes in the mechanics of the foot due to footwear [142].

One advantage of in shoe plantar pressure measurement is the ability to measure multiple, consecutive steps [142]. Being able to collect multiple steps is beneficial because human gait is variable and no two consecutive steps are the same [143]. To overcome this variability and facilitate the comparison of different experimental footwear conditions, a number of footsteps must be recorded. This allows us to produce an average step that is assumed representative of the wearer. **The number of steps required to provide a valid description of plantar pressure in a specific shoe condition is currently not known**, since past research has only investigated this in one footwear type and for a very specific population which are known to have an adapted gait [26]. Furthermore, each shoe type used is likely to increase or decrease the variability of gait by a different amount. This variability is likely to be emphasised when participants are asked to wear footwear that have design features which they are unfamiliar with or rarely experience. For different levels of variability the number of steps required to provide a valid description of plantar pressure may differ.

Prior to a participant demonstrating their underlying gait pattern in a specific shoe, it is likely that a participant will require a period of acclimatisation to familiarise themselves with the shoe. During this acclimatisation period an increased level of variability can be expected in the gait cycle and as a result it is common for researchers to provide the participant with a period of time to familiarise themselves [25]. It is important that the investigator does not collect data until the acclimatisation has transpired and a more consistent gait pattern has been established. This acclimatisation period might differ for different footwear, especially if the shoe is very different from the footwear typically worn by a participant.

Protocols used in prior research to acclimatise to footwear vary considerably and often only scant details are offered. Some studies require the participant to familiarise themselves with the study protocol rather than the footwear being tested [17, 92, 144, 145], others had participants acclimatise to footwear walking on a treadmill but collected data during over ground walking [72]. Other investigators allow a period of time between conditions but do not explain the purpose of this period or what each participant did [65]. There are studies which allow the participant to acclimatise to each footwear condition [25] and 5 min is the most common period of time provided. The variation in methodologies highlights the lack of understanding of the acclimatisation effect. Furthermore, no previous studies have reported quantitative criteria to define when a participant has acclimatised to a specific shoe design.

The exact length of this acclimatisation period, or the number of steps required to acclimatise to unfamiliar footwear, is not known. One objective of this study, therefore, is to identify the **number of steps a participant requires to become acclimatised** to a range of footwear. The second objective is to identify the **number of steps that are required to**

determine a valid description of plantar pressure data i.e. data which is representative of the way the participant walks in a particular shoe.

3.2. Pressure Literature Review

3.2.1. Plantar Pressure and how it is measured

Plantar pressure is force measured over an infinitesimally discrete area on the plantar surface of the foot. When the foot makes contact with the ground a force produced by body weight is exerted onto the ground. To prevent you from sinking through the ground, the ground must apply a force equal and opposite to body weight on to the foot, called the ground reaction force. By considering this force over an infinitesimally small area we are able to substitute force for pressure and consider how the external load is distributed over the various plantar structures of the foot. Orthopaedic surgeons [22], prosthetists [146], orthotists [133], footwear manufacturers [38] and biomechanics researchers [147] have all used plantar pressure measurement to help understand the foot and the mechanisms that affect it. This knowledge is required to improve the health of the foot and the performance of the products the foot interacts with (or is replaced by in the case of prosthetics).

There are two main components of loading experienced by the plantar surface of the foot: vertical pressure and shear. It has been confirmed that shear distribution may explain the variation between vertical peak pressure location and the location on ulceration [148]. Unfortunately, the technology available to measure shear pressure is limited and normally consist of a platform [148] and thus cannot be used to measure in shoe pressures. Instruments that are designed to be used inside footwear are currently only able to measure vertical forces and thus vertical pressures, and at discrete locations using 10 X 10 X

2.7 mm sensors [149]. The issues with using such systems are that the location at which data is collected needs to be chosen before data collection with no guarantee that the correct location will be chosen. Even if the correct location is chosen the device may migrate during testing. Furthermore, the very act of including the sensors within the shoe will change the relationship between foot and shoe and thus the biomechanical phenomena being investigated.

There are many ways to investigate the pressure on the plantar surface of the foot. Early and crude approaches to barefoot pressure measurement include ink impressions produced using products such as a Harris mat [150] but it is now routine to use mats comprising matrices of force sensors, such as the Emed platform (Novel Gmbh, Munich, Germany) [151]. However, investigations on the effects of shoe features using devices external to the shoe, such as pressure mats, are of limited value. This is because pressure mats do not provide information on the pressure at the foot-shoe interface. They are single foot strike systems and therefore inhibit the investigator from collecting continuous steps, thus increasing the time required to collect sufficient steps to produce valid plantar pressure data, formulated from numerous steps, for each experimental condition [139].

There are many techniques for measuring the pressure inside footwear. In 1947, Schwartz and Heath [152, 153] used small capacitive disc transducers to investigate plantar loading. These where attached to six locations on the plantar surface of the foot: at the great toe, first, third and fifth metatarsals, and both the medial and lateral aspects of the heel. Following this, a number of groups investigated a range of techniques to record pressure on the plantar surface of the foot [154-158]. A full description and appraisal of the types of pressure measurement devices available has previously been provided by Lord 1988 [159] and more recently this has been updated Urry 1999 [160]. There are many devices that can be used to measure the pressure inside the shoe, from microcapsules full of dye to piezoelectric methods, and an appraisal of these approaches have also been reported in detail [142]. Using discrete sensors at specific anatomical sites keeps the number of sensors required low, but requires accurate locating of the sensors before testing. It assumes there is a strict hypothesis supporting such limited measurement in the surrounding areas of the foot. Also, the stiffness and thickness of the sensors will often be different to the rest of the foot bed and therefore the sensors will act as a 'foreign body' in the shoe, changing the mechanical conditions which are being measured [159]. Finally, issues related to incorrect placement of sensors can lead to poor data, often due to sensors migrating during the experiment [142].

To address these difficulties, technical advances focused on the development of matrices of sensors that cover the entire plantar surface, thereby limiting the amount of "dead space" in between sensors where loads applied would remain unmeasured. This led to the development of sensors based on two 50 µm copper foils placed either side of a sponge rubber sheet (~2mm) that covered the entire plantar surface [161]. Of the wide range of insole pressure devices available, two devices have emerged as the most popular: f-scan (Software v. 3.4, Tekscan. Boston, MA) and Pedar (Novel Gmbh, Munich, Germany). Pedar was developed based on the work of Nicol & Hennig [161] and is often reported as the better of the two devices because it has greater accuracy and a lower variability (60%, 20% and 22% lower variability at the heel, central metatarsal heads, and great toe respectively) [162], as well as its ability to verify the measurement of each sensor [147]. It has been shown that the Pedar system has the best accuracy and precision assuming: (1) it has been recently calibrated according to the manufactures guidelines, (2) it is operating between 50-500kPa and (3) when the data is collected within a few seconds of the pressure being applied [163] i.e. standing for long periods whilst using the insole will generate sensor drift. When these requirements are adhered to the per cent errors range is -0.6 to 2.7, which is dependent on the specific pressure loads, as well as the magnitude, found by taking the lower bound from the upper bound, of the 95% tolerance intervals between 13.5 and 18.7% [163].

A matrix of sensors covering the plantar surface of the foot produces a lot of data (99 sensors per foot, each recording at 50Hz). This must be reduced into useful subsets and specific variables extracted, only then can hypotheses be tested. A common approach is to divide the pressure measurement insole data into primary level anatomical regions (masks), which can be especially useful if the research is seeking to identify changes in pressure at specific sites (e.g. under metatarsal heads). However, this "masking" approach introduces artificial boundaries into the data that whilst anatomically relevant may not exist in functional terms.

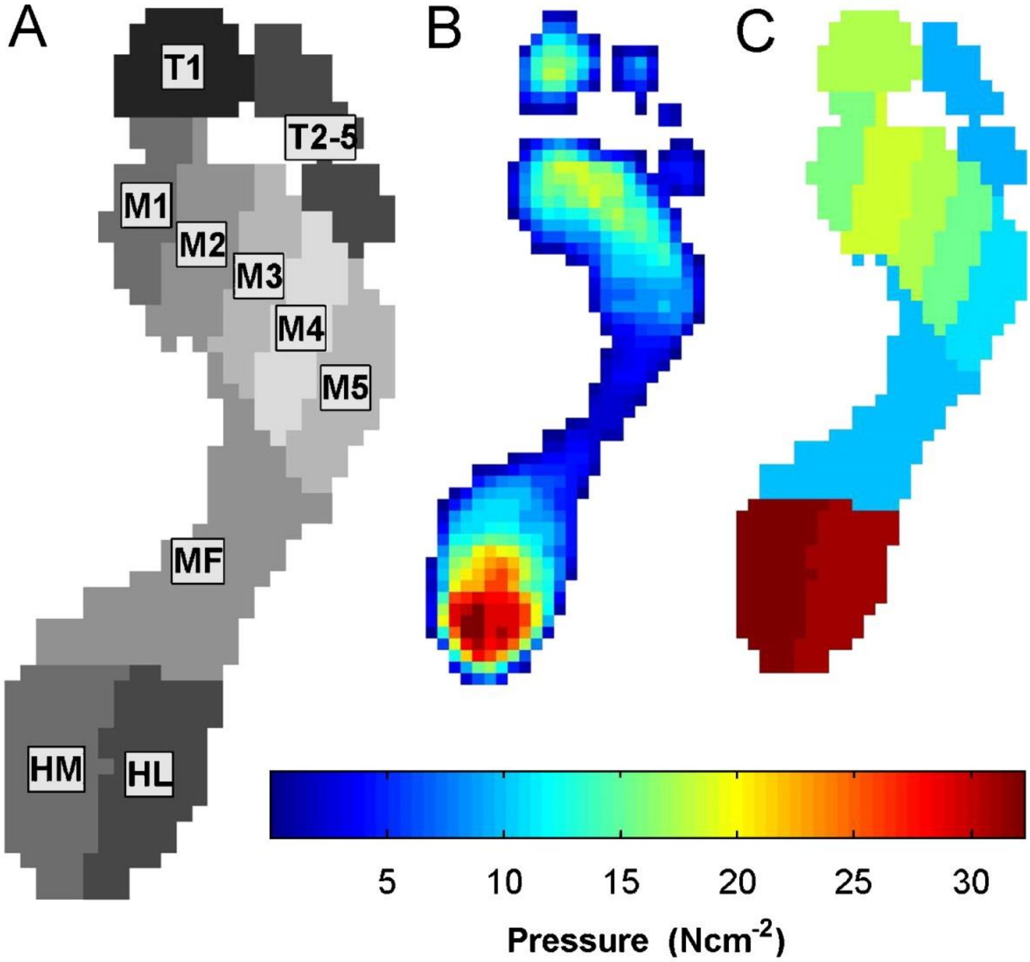

Figure 32: comparison of regional peak pressure and region of interest taken from Pataky et al 2008 [164]

Masking also assumes that you know the location where changes in pressure will occur. It has been shown that masking the foot by anatomical region, e.g. rearfoot, midfoot, forefoot, leads to potential loss of useful information in the pressure data [165]. The two types of data analysis (pixel and regional) can be seen in **Figure 32**. Using regional analysis may mask differences between individuals or experimental cases that exist at a pixel level but not at a foot region level. This occurs because data is averaged across the region (e.g. all of the forefoot), or represents just one pixel in that region (e.g. peak pressure) and thus ignores the data in all the other pixels. In the only published case addressing this concern, statistical parametric mapping, which uses individual pixel data, found positive correlation between peak pressure and walking speed in the midfoot and medial proximal forefoot for traditional ten region subsampling, but negative correlation in the midfoot and proximal forefoot when using pixel data [164]. So large are these effects that it has been shown that in the regional analysis, the location of the peak pressure defined by the centre of a region, will differ in location of the when using pixel data in 80% of cases. Furthermore, if the location of the peak pressure, from pixel data, falls on the location of a regional boundary, of regional data, with a probability of 65%, which means the regional mask technique cannot have reported the peak pressure location correctly [166]. These findings have led researchers to conclude that regional masks data is biased because its regionalisation scheme delineate the observed data according to the anatomy instead of the its geometric properties [166].

To overcome this problem *statistical parametric mapping* has been applied to plantar pressure data [164]. This produces a continuous statistical map based on individual sensor data rather than predetermined groups of sensors. These maps represent the original foot pressure data in image form and direct comparison of maps between experimental conditions can identify statistically meaningful differences (i.e. $p<0.05$) in pressure distributions. This has the particular advantage of making no assumptions about where under the foot the differences in pressures might occur, which might be valuable since the foot is a complex deformable structure and its interaction with the shoe is complex and perhaps highly person specific.

Regardless of analysis approach, comparisons assume prior knowledge of the key variable to extract from the pressure data. A wide range of variables have been derived from plantar pressure data: peak pressure (e.g. at a specific sensor, or in a specific mask, at any point during the gait cycle) [167], average pressure (e.g. at a specific sensor, or in a specific mask, over the entire gait cycle) [168], pressure time integral (e.g. at a specific sensor, or in a specific mask) [91], force [169], contact area [168], force time integral [91], mean area [170], and contact time [167]. Of these the most commonly reported are the peak pressure and the pressure time integral. Peak pressure is popular since it is assumed that high loads are damaging to tissue and might cause pain or more significant destruction, leading to ulceration [16, 171]. This is of interest in this thesis because in following studies we will investigate how shoes affect comfort, and comfort is often regarded as a point on a much wider pleasure-pain scale. The peak pressure time integral recognises that instantaneous application of high pressure might not always be a critical factor, whereas application of lower pressures but over longer time periods might also cause tissue damage. Static, barefoot standing has produced average plantar pressure values of 70kPa and peak plantar pressure values of 140-175kPa [172] with peaks of over 300kPa during walking [173] which is far in excess of the required pressure shown to generate skin and nerve damage. To exceed capillary pressure and thus put the tissue at risk of ischemia, pressures averaging only 4 – 4.7kPa are required [174, 175], and that which has been shown to effect nerve impairment in rabbits [176].

A key difficulty in choosing a suitable variable is that the underlying relationship between clinical conditions and symptoms, and plantar pressure variables are not well understood. The assumed association between high loads or prolonged application of loads and tissue damage seems a reasonable starting point. In addition, some variables are not independent of each other. Prior work has now demonstrated that peak pressures and the pressure time integral are closely correlated and reporting both is often redundant [93]. It has also been reported that the plantar pressure parameters; peak, mean and impulse can be compared both across studies and parameters [177]. As a result it has been suggested that using a smaller set of parameters is more effective at capturing the biomechanical behaviour being observed [177].

3.2.2. Sensitivity of plantar pressure data to footwear design

Due to the high sensitivity and accuracy of in-shoe pressure measurement systems to changes in the loads at the plantar foot surface and shoe interface, many studies have proven that plantar pressure is sensitive to changes in footwear design. For example, some have reported that as heel height is increased the loading of the forefoot increases [9, 24, 91, 105]. Others have shown that changing the shoe rocker angle and location can change the location of peak pressures [77], often to off load the high regions of pressure which can be detrimental to those with diabetes [178]. Also, relatively small changes in design or fitting such as lacing [119], heel seat length, and heel wedge angle [110] have all been shown to change the loading in the shoe.

It is commonly reported that the loading of the forefoot is increased in high heels, although this occurs almost exclusively on the medial side [9, 91, 105]. Knowing the exact location that plantar pressures are high may allow changes in footbed material or geometry to target this area to avoid risk of pain or injury. Despite this, relatively few studies have taken shoes that are popular with consumers but historically assumed bad for the foot, such as high heels with narrow toe boxes, and looked to make relatively small design changes in order to improve pressure and/or comfort. Studies which have tried to isolate just one shoe feature and analyse it's effect when systematically changed, have focus on; foot bed design, changing heel seat length and inclination [110], and using inserts with varied heel cups, arch support, and metatarsal pads [9]. Unfortunately, in most cases the materials used are not clearly specified despite the fact they too will affect pressure [179, 180]. This is an example of how improved reporting of the footwear tested would benefit the field.

Research has mostly focused on ways that shoes can make relatively large changes to the pressure applied to the foot, namely focusing on regions of peak pressure and their associated health risks. In particular, many investigations have focused on rocker shoes and plantar pressure under the forefoot. These studies primarily adjust sole apex location, apex angle and subsequently toe spring [77]in stiff soled shoes. Despite the reported findings of past studies, without stringent control of the remaining footwear features comparisons of pressure data may not reflect the true effect of the features investigated.

All studies reported in the literature show that if any change is made to the shoe, plantar pressure will also be changed, as can be seen in Table 2. This is unsurprising if you consider the intimate contact between shoe and foot, and consider the foot and the shoe as a single and integrated mechanical system. Thus, change in one part of the system has the inevitable consequence of directly affecting other parts. As a result it can be assumed with confidence that any shoe feature changed will have some effect on the plantar pressure recorded. Plantar pressure is thus a suitable measure with which to evaluate loads applied to the foot and how footwear design features affect these loads.

Table 2: Studies of footwear effects which used the Pedar plantar pressure insole

Paper [reference]	Participant type (number of participants)	Data type	Footwear feature modified	Acclimatisation period provided (number of steps collected)	Changes in plantar pressure
Jordan & Bartlett 1995 [17]	Healthy male (15)	Perceived Plantar Comfort, peak pressure, plantar force, plantar area, plantar pressure-time integral, plantar force time integral, peak dorsal pressure, total dorsal force, perceived upper comfort, perceived upper comfort in lacing region.	A range of commercial footwear	It only states "Habituation was allowed" and no further information is provided.	Increased total plantar force and force time integral related to a decrease in perceived comfort, decreased dorsal forces and pressures related to decreased upper comfort. Pressure can be used as an indicator of comfort.
Lan-Yuen Guo et al. 2012 [181]	Healthy female (13)	Peak Plantar pressure	Base of support	"After a familiarization period with the walking speed, we collected…"	Heel width is inversely proportional to plantar pressure at the hallux and toe in high heels. Running increases pressure at the medial forefoot.
Snow et al. 1992 [105]	Female (45)	Peak plantar pressure, pressure distribution, time to maximum pressure, support time, rate of loading	Heel height (1.91, 5.08, and 8.26 cm) the low and medium shoe uppers where made of leather whilst the high heeled shoe upper was made of vinyl	"subjects were allowed to practice until they could walk at a steady rate of 1.4 m/sec"	Increased heel height (1.91 cm -8.26 cm) increased peak pressure from 332.25 to 480.75 at metatarsal head one, decreased time to maximum peak pressure under the metatarsal heads from 376 to 241 ms, whilst also increasing the rate of loading for the metatarsals during early support (from 2.59 to 7.51 at metatarsal head one). Height increased

Paper [reference]	Participant type (number of participants)	Data type	Footwear feature modified	Acclimatisation period provided (number of steps collected)	Changes in plantar pressure
					load to a more uniform distribution of pressure beneath the forefoot
Nyska et al. 1996 [91]	Healthy female (10)	Total contact area, maximal plantar force, peak plantar pressure, duration of plantar contact time, plantar pressure-time integral, force-time integral, instant peak pressure, instant peak force.	Their own highest and lowest heeled shoes	"they walked at a regulated speed of 4 km/hr for at least 5 minutes until they felt comfortable"	High heel shoes increase loading under forefoot, particularly the medial forefoot and relieves it beneath the heel, lateral forefoot showed decreased contact area, forces, and peak pressures, whilst, the medial forefoot had higher force-time and pressure-time integrals.
Liping Wang and Jianshe Li 2005 [182]	Healthy females (12)	Maximum pressure, mean pressure of masks	Bare foot and various heel heights (flat heel, 4.5 and 9 cm heel)	(30 steps collected to produce an average) there was a 10 min period between trials but it does not state if this is a wash out period, an acclimatisation period or served another purpose.	The area of applied pressure decreased with increased heel height, pressure at the medial forefoot increased, whilst pressure decreased a the lateral forefoot and heel with increased heel height whilst
Queen et al. 2010 [144]	(17) healthy males and (17) healthy females	Maximum force, contact area, contact time	Gender comparison, type of running shoe	Subject allowed to familiarise themselves with the lab and testing procedure for 3 to 5 minutes.	Shoe design should be gender specific in an attempt to prevent injuries.
Stewart,	(4) male, (6)	Minimum, maximum, and	Comparison of a	No information given.	Significant shift in pressure to

Paper [reference]	Participant type (number of participants)	Data type	Footwear feature modified	Acclimatisation period provided (number of steps collected)	Changes in plantar pressure
Gibson, and Thomson 2007 [168]	female	mean peak pressure of the toes, forefoot, midfoot and hindfoot, and total contact area.	control (participant's own shoe) and rocker bottom MBT shoe.		the forefoot.
Lee Yung-Hui, and Hong Wei-Hsien 2005 [9]	Healthy females (10)	Peal pressure, impact forces, comfort rating,	Heel height (1, 5.2, and 7.6 cm), insole type (shoe only, heel cup, arch support, metatarsal pad, and total contact insole), pressure, impact force, perceived comfort	Walked on a treadmill for 5 minutes despite the tests being conducted on flat ground, no other acclimatisation period mentioned.	Increasing heel height increases medial forefoot pressure, impact force, and perceived discomfort during walking and shoe inserts can be used to counteract this
Speksnijder et al. 2005 [24]	(10) healthy females	Peak pressure, pressure time integral, maximum force, force time integral, contact time, contact area	Heel height of participant's own shoes (high 5.91, low 1.95 cm)	25 steps stored for further data analysis. Subjects allowed to walk around for several minutes before testing each shoe.	Increased heel height increases peak pressure and pressure time integral of the medial forefoot and the peak pressure of the central forefoot.
Wegener et al. 2008 [141]	Male and female with bilateral cavus feet and run at least 20 km/ week	Peak pressure, pressure-time integral	Three footwear conditions: two neutral cushioned running shoes and one control condition	Five minute acclimatisation period per shoe. 9 steps from a random foot were obtained for reliable data and to satisfy the independence requirements for	Neutral cushioned running shoes were effective at reducing pressures of cavus feet.

Paper [reference]	Participant type (number of participants)	Data type	Footwear feature modified	Acclimatisation period provided (number of steps collected)	Changes in plantar pressure
				statistical analysis	
Wei-Hsien Hong et al 2005 [109]	Healthy young females (20)	Comfort rating, ground reaction forces (x, y, z), peak pressure, impact force	Six conditions consisting of: Three heel heights (1 , 5.1, and 7.6 cm) and a total contact insole	Before each condition the participant walked on a treadmill for five minutes to become habituated to the shoe and walking speed. Data from three gait cycles were collected.	Increased heel height reduces comfort, use of a total contact insole improves comfort of a high heeled shoe.
H Chens et al. 1994 [183]	male (14)	Maximal force, peak pressure, pressure-time integral, force-time integral, maximal area, centre of force path (separate x and y components)	Four insoles (polyethylene with flat heel shape, polyethylene with spherical heel shape, cork with flat heel, EVA with spherical heel)	Three trials for walking and five for running were collected. No acclimatisation period was outlined.	For walking there were significantly higher pressures and forces in the midfoot area and significantly lower pressure in the medial forefoot and hallux when wearing the most comfortable insole.
Burnfield et al. 2004 [135]	Healthy adults, 10 male, 10 female	Peak pressure, mean peak pressure, walking velocity, peak force, pressure-time integral, contact area	Walking speed (57 m/min, 80 m/min, and 97 m/min), barefoot and the participant's own footwear	Prior to recording the participant was able to practice the three walking speeds, it is not clear if all three were practiced at the start of the session or before the trial of the particular speed	Increase in walking speed increases pressure under all foot regions except the arch and lateral metatarsal. Pressure is higher when barefoot than when the foot is shod.
T Stöggl et al. 2010	6 males, 6 females,	Foot force minimum, peak forefoot force, peak medial	10 week training effect of a MBT shoe	3 minute period for accommodation to	35% higher variability in plantar pressure distribution

Paper [reference]	Participant type (number of participants)	Data type	Footwear feature modified	Acclimatisation period provided (number of steps collected)	Changes in plantar pressure
[145]	healthy sport science students	foot force, impulse of forefoot force, impulse of rear foot force, impulse of medial foot force, mean centre of pressure, plus kinematic variables	compared to a conventional running shoe	test situation. 20 gait cycles were recorded but it does not state if all were analysed.	with unstable shoe compared to conventional shoe, which decreased to 30% after training period to almost equal variability.
K E Fiedler et al 2011 [184]	20 participants	Comfortable walking speed, peak pressure, average peak pressure, pressure time integral, reported pain, perceived in-shoe displacement	Effect of lacing tightness	5 minute acclimatisation period at the start of data collection.	Loosening laces increase peak pressure and pressure time integral under the forefoot, Perceived displacement is also increased.

3.2.3. Review of Past Protocols for Collection of Plantar Pressure Data: (1) The Number of Steps that are required for valid data.

An advantage of in shoe plantar pressure measurement is, the ability to measure multiple and sequential steps [142]. Being able to collect multiple steps is beneficial because human gait is a naturally variable phenomena and no two steps are the same [143]. The body is in a continual state of dynamic imbalance [185] and adjustments are continually made resulting in variability in foot placement (e.g. stride length, cadence) which affects the internal moments and joint rotations [185-189]. The coefficient of variation for stride frequency and stride length are relatively low at approximately 3%, however this can be affected by walking speed [186]. Similarly, it has been shown that there is variability in the moments around each of the lower limb joints. In the frontal plane between trials that are a few minutes apart, it has been found that joint variability is: ankle abduction moment 2.1 Nm, ankle adduction moment 2.4 Nm, ankle mid-stance moment 2.3 Nm, and in the sagittal plane peak ankle plantar flexing moment 49.5 Nm, peak ankle dorsiflexion moment 4.9 Nm, ankle mid-stance dorsiflexion moment 3.3 Nm [190].

Due to the natural variability in gait it is necessary to evaluate multiple steps in order to form a valid representation of plantar pressure. Collecting too few steps will not provide a valid representation of the distribution of load under the foot and will prevent valid comparison of different footwear types, or differences between participant groups. The difference between two randomly chosen steps can be large because of the many processes that take place during gait. When data has high variability it is common to take many samples of the data to establish a representative average. When the number of samples taken is too low random outliers in the data can significantly affect the standard deviation, therefore, the more samples collected the more representative of true value the mean and the standard deviation become.

By contrast collection of too many steps may not necessary improve data quality but instead wastes participant time, and may introduce participant fatigue in experiments with many footwear conditions. This may adversely affect data quality in the later experimental conditions and thus introduce fatigue as a confounding variable. This in turn may make comparisons between data collected early and later in a data collection session invalid. Furthermore, it is arguably unethical to collect data that is known to not be required or that may become useless.

The issue of the number of steps of plantar pressure data required has not been thoroughly investigated. One related estimate suggested 400 steps might be required, but this was for valid kinematic data when walking on a treadmill [187]. This study in fact used steps from both feet, a practice that is not common in pressure data and thus a figure of 200 steps (or less since the variability of one foot may have no correlation to the other making this value higher than necessary) may be more suitable when using one foot.

Past research has shown that those with diabetes and wearing bespoke footwear are only required to provide twelve steps [26]. The type of footwear may also be a factor affecting variability between steps. Barefoot walking has been shown to require 6 steps to reach a steady state, whilst when wearing shoes the required number of steps to walk at a steady speed was 5, orthoses can further reduce this figure to 4 steps [191]. For plantar pressure data it has been reported that just eight steps are required for valid [147] when walking speed is mechanically controlled using a treadmill. Variations in walking speed may be greater when the participant walks freely on a flat surface and in contrasting footwear designs and thus more steps may be required.

To date, only one plantar pressure study has investigated the number of steps required for over ground walking. This study focused on people who have diabetes and sensory neuropathy, who were walking whilst wearing custom made rocker shoes designed for those with diabetes [26]. The investigation had two outcomes; how many steps were required for reliable data, and the number of steps required for valid data. *Reliable data* (data that consistently attains a value within a similar range, in this case data during the acclimatisation period will be unreliable) was a within subject investigation design. Whilst, *valid data* (data that provides a true representation of what is occurring, in this case data will be valid when it produces a representative average step) was a between subject investigation. When all participants are included in the analysis (some were excluded from some of the analysis presented but the rationale for this was not clear) this study shows that just 3 steps were required for reliable data and up to 17 were required for valid data. However, only 20 steps were taken in this study and thus the assumption was that no more than 20 would ever be required. From a statistical aspect it was not clear if cyclic patterns or other variations in gait were considered. Furthermore, in this study it was reported that participants required 17 steps, however the sample was only 20 steps so it is likely that the data converged due to the small sample size and not because the participant's gait had reached a steady state. Finally, it is not appropriate to use results from studies which investigated individuals with diabetes since they may walk significantly slower (62.2%

reduction) and with a wider stance (134.9% wider) compared to healthy control participants [192]

Research has shown that compared to healthy individuals people with diabetes and sensory neuropathy can exhibit an altered gait pattern [193, 194]. Furthermore, rocker footwear have unique features including a very stiff sole and a distinct angular sole profile, both of which can effect gait [195] and this limits the generalisability of results for other footwear types and healthy individuals. Therefore, there remains a need to establish the number of steps required to collect valid plantar pressure data, when testing healthy participants wearing a range of retail footwear.

As can be seen from Table 2 there is inconsistency in the number of steps collected during gait studies, from as few as 3 gait cycles [25] to 30 gait cycles [182]. If the information provided by the previous diabetic literature [26] also applies to healthy participants then very few, if any investigations record the necessary number of steps. At best many investigations waste a lot of time but at worst their results are not valid because insufficient steps are collected to produce effective representation of gait. Of all the papers in Table 2 only one provided a reason for the number of steps recorded. However the sources it used consist of a predominately statistical approach [196] rather than results of testing participants, and data from a treadmill [147]. Furthermore, since it has also been shown that footwear design has an effect on gait variability [145], the number of steps required to acclimatise and produce an average representative step will likely change for different footwear types.

For the purposes of this thesis, there is a need to investigate the minimum number of steps required for healthy participants to reach steady state and to provide valid data and to understand how these will change across a range of consumer related footwear types. The additional requirement of a footwear range is required, because each shoe type used could increase or decrease the variability of gait by a different amount. This might especially be the case if participants are asked to wear footwear that has design features that are very different to the footwear they normally wear. For different amounts of variability the number of steps required to provide a valid description of plantar pressure may differ.

3.2.4. Review of Past Protocols for Collection of Plantar Pressure Data: (2) Acclimatisation Period Required

When a participant is subjected to a new experience such as a test environment or a shoe to which they are unfamiliar, it is reasonable to assume that they will undergo an acclimatisation period [187]. This is especially the case if a shoe design is very different from the footwear they typically wear. During this time the natural variability of gait may be increased and thus provide the researcher with data that is not representative of the actual effect of the shoe. Due to this variability it is important that the investigator does not collect data until this acclimatisation period is complete and a consistent gait patterns has been established.

To ensure acclimatisation is complete it is common for researchers to allow a participant to 'practice' walking. For example, a participant may be given five minutes to walk on a treadmill before data is collected [147, 197], or complete two laps of the study area [180]. However, whilst the period given to acclimatise has been reported, it is not clear if acclimatisation was achieved nor what variability the period given is presumed to eliminate. For the purpose of this thesis, the term acclimatisation period will be used to describe the following: the period required for the variation in plantar pressure data over successive steps to no longer materially change. So it could therefore be said that the data has achieved a steady state and any variation seen in step to step data is that which is normally observed in normal walking, for a specific participant. The exact length of this acclimatisation period (the number of steps required) is therefore unknown. Since different footwear might create different perturbations in walking they may also require different periods of acclimatisation. This will vary depending on the difference between the footwear worn in a study and the footwear typically worn by a participant. This is because the acclimatisation period is the result of the response from the motor control system to the new stimulus it experiences from the unfamiliar shoe. As a result gait variability increases for an individual that have disorders which affect the basal ganglia, such as Parkinson's disease as well as other neurological disorders such as Alzheimer's disease [198, 199] Thus, the acclimatisation period may be footwear and participant specific.

3.2.5. Aims

There were two aims to this study:

1. To investigate the number of steps required to produce an average step that is representative of normal gait.
2. To investigate the number of steps required for a participant to acclimatise to a range of footwear types.

3.3. Experimental design and procedure

An experiment was designed and implemented that involved male and female participants walking in a range of retail footwear. The footwear was chosen so that they presented different challenges to the participants' gait. It was assumed that each challenge would require different periods of acclimatisation and a different number of steps to produce valid description of plantar pressure data, and thus improve the generalisability of the results. In the experiments plantar pressure data was collected from the very first step taken in the footwear, and continually for over 400m of walking (20 lengths of a 20m test area, steps were removed for the turning phase at each end). The assumption was that 400m of walking would provide data for the acclimatisation period and sufficient opportunity for participants to walk for an extended period in their steady state (i.e. when fully acclimatised to the footwear). Thus, both research aims could be addressed through this data.

3.3.1. Participants

Male and female participants were recruited from the student and staff population of the University of Salford. The target sample was 10 females and 10 males. Recruitment was via email and posters billed around the university campus.

The inclusion criteria were:

- aged between 18 and 45
- no known foot or lower limb injuries or visible abnormalities
- Able to walk unaided for 2.5 hours.
- Have a shoe UK size of 5 or 6 (female), and 8 or 9 (male)

3.3.2. Instrumentation

<u>The Pedar Device</u>

In-shoe plantar pressure was recorded using the Pedar-X system (Novel GMbH, Munich, Germany). The insoles were placed in the shoes between the sock and shoe footbed and connected to the data logger that is attached to the participant via a waist belt. From the data logger the data is transmitted wirelessly via Bluetooth to a laptop computer. The insoles comprise of 99 sensors under the plantar surface which are housed between two layers of rubber sheeting, giving the Pedar insole a total thickness of 2.2mm. The sensors have an operating range of 20-600KPa and are sampled at a sampling frequency of 50 Hz. The insoles tolerate some bending due to curvature of shoe soles, however the manufacturer has recommended that the insoles are not bent beyond a radius of 25mm to avoid damaging the sensors. Bending the sensors may also apply stress to the insole thus inducing artefacts in the recorded pressure data.

The Pedar system was calibrated before the study and repeated after approximately 4 participants or whenever there had been a period of inactivity of more than three weeks, in accordance with the manufactures guidelines. Calibration involves placing the insoles into the Pedar's Trublu calibration device, which consists of an inflatable sack in a steel housing. By placing the Pedar insoles inside the housing it is possible to apply a known controllable load evenly across all the sensors by increasing the pressure inside the inflatable sack, compressing the sensors between the sack and the housing (a sleeve is placed between the housing and the insoles to help protect them and correctly position them). The calibration process consists of incrementally increasing the pressure inside the sack whilst measuring the electrical signal produced by the sensors and thus characterising the pressure/electrical signal relationship, the recorded values can then be compared to those recorded during data collection so that the applied load can be calculated.

For the purposes of completeness a review of the performance of the Pedar system is presented here. Problems with Pedar include the relative ease the equipment suffers mechanical breakages of the sensors and leads, which can be caused by repeated loading at high pressures [147, 163]. Poor sensor performance can be due to the warm and humid in shoe environment [147, 169], as well as a constant load over an extended period [142, 163, 200] which can be expected inside a shoe. At early and late stance pressure data is lost because the sensors can only measure pressure that is applied normal to the sensor surface in the direction of their load cells [169]. This can also be the reason that data is lost when the insoles are placed on top of foot beds that are highly contoured [147]. Like all measurement devices Pedar operates in an optimal range, as a result studies have shown that at relatively low pressure (<50kPa) measurement error can be high (16%) [200]. Whilst Pedar is reported to have a measurement range of 20 -600kPa it has been recommended that values below 35kPa are not measured [163].

It is important to have reliable (consistent, precise) and valid (accurate) data. Reliability represents the consistency of the measurement over time when the true value being measured has not changed. Repeated measures of the same phenomena thus produce the same data. Whilst a measurement may provide valid data, if the instruments do not provide data that is reliable it is of no use [200]. Accurate or valid data is data that is within a predefined percentage error of a true value [163].

A number of studies have investigated the reliability and validity of plantar pressure devices [22, 143, 147, 162, 163, 170, 200-204], and many have compared the Pedar (a capacitive device) to the f-scan (a resistive system). All have reported that Pedar as superior [147, 162] and some have questioned the usefulness of f-scan as a scientific tool [200]. Results have shown that the Pedar insole has a maximum percentage error of 19% at 300N and a maximum of -8% at 1000N [22]. The large error found in this study when there is a low applied load is consistent with other studies [163, 200] and has led to the recommendation that values below 35kPa be removed due to unreliability of the data. It has also been showed that there is a mean day to day difference of 3% [22]. It should be noted that this study collected data from a large number of gait cycles (1200) and reported drift of up to 62N over the 1200 steps. This drift however was deemed negligible after shorter periods of data collection of between 5 – 10 minutes [22].

Drift is defined (in this case, in context to plantar pressure measures) as an undesirable change over time in the recorded force data that is unrelated to the input load [22]. The drift found has been identified as both an offset drift and a gain drift [22], with apparent creep of up to 17% over a 3 hour period [205]. It has even been reported that data below approximately 35kPa should not be recorded [22, 163, 200] and the best accuracy is recorded between 50 – 500kPa [163]. However, for short trials of just a few steps most investigations have reported that the creep is negligible. This is not the case for trials of more than 8 steps and as a result algorithms have been produced to correct the drift [22, 169, 205]. Some drift can be removed by allowing the insoles to have a warm up period of one hour and then recalibrating the insoles. However, with limited battery power and when requiring participants that are a range of shoes sizes in back to back testing, this is not always possible. Due to the different requirements of the testing procedure in this thesis compared to past studies (i.e. continuous walking trials over 400m, back to back tests of different participants, and a range a shoe sizes used during the course of a day), it was not possible to comply with the protocol of past studies [22]. To better explore whether and how drift might affect the testing in this study and thesis, a pilot study was undertaken to understand how to quantify and correct for drift.

Pilot Investigation

It was thought that if there was a drift in the data collected and it was due to the sensors, then it would most likely be due to sensors providing 'ghost values'. Ghost values in this case are those that are above zero despite the sensors being unloaded. This is quite likely since, just like any electrical signal, the signal produced by the Pedar system is susceptible to noise. Any noise, however it is created, would result in a zero reading becoming a higher value, and thus a ghost value. It is unlikely the foot will load every sensor at any given time and therefore in the event of the Pedar sensors reporting ghost values the total area of the insole that is loaded will increase. This will be particularly apparent during swing phase since few sensors should be loaded. Thus this pilot study was designed to investigate if the Pedar system drifted and in the event of a drift distinguish if this is due to ghost values increasing the loaded area and finally to distinguish a method of rectifying this.

Method:

Twenty young adults (10 male and 10 female, mean (SD) age = 28 (7.1) years, height =1.692m (0. 074); mass = 69.9kg (14.9)) participated in this study. Upon arrival the participant was given the opportunity to read the testing protocol, told what was expected of them and informed written consent was taken.

To enable the participant to familiarise themselves with the testing procedure and the required walking speed (1.2 $m.s^{-1}$ ±5%), they walked continuously along the length of the testing area for five minutes whilst wearing their own shoes. During this period the Pedar insole was inside the shoes to enable measurement sensors to acclimatise to the environment inside a shoe.

Once acclimatisation to the walking speed was complete the insoles were removed from the shoes and laid flat on the ground. Once flat the zero calibration was completed i.e. the load on the insole was set at 0kPa. The zero calibration is required before each trial as part of the protocol recommended by Pedar, however it is normally done whilst the insole is inside the shoe and the foot is off the ground (i.e. non weight bearing). However if you do this you cannot be sure there was no loading on the insoles when they are zeroed, making it difficult to assess if there has been any drift and by how much the sensors drift. In this pilot study we wanted to compare pre walking and post walking insole measures to identify whether any drift had occurred. In doing this it was necessary to remove the foot and shoe as both are variables that might also change over time and therefore measures of the insole outside of the shoe were required, pre and post walking.

Once the zero calibration was complete the insoles were placed into the shoes. The participant tied their own laces and the walking trial began. Each walking trial consisted of 20 lengths of a 20 meter test area and the total test for each condition took between 11 and 12 minutes. Once the trail was complete the participant was seated, their shoes were removed, and the insole taken out of the shoes and laid flat, the process was then restarted for the next shoe condition. All shoe conditions were tested as each would expose the foot and shoe to a different environment and it was not known how each environment would affect the results. This process was repeated for all the shoes that would be later included in the full study, which is described in detail later in this chapter.

Pilot results and discussion:

Figure 33 shows the total area of the insole that is activated throughtout the entire data collection period for one shoe and it shows a steep incline in the pressure during the swing phase (regions of low pressure), shown by the swing phase drift line in the figure. During the first few steps aprroximaley 10% of insole is activated during swing however for the last few steps this figure has doubled to over 20%. Whilst it is possible that the foot would swell after long periods of walking the drift observed begins immediately, also a 10% increase in contact due solely to the foot expanding, after just a few minutes would be unpresidented. It is then, more likely that the drift is due to the sensors and not the foot. The 10% increase shows that during the course of data collection the number of sensors activated during swing phase steadily increases. A smaller but much reduced drift is also present in the loaded phase, where approximaely 82% of the insole was loaded for the first step which changed to 86% for the final steps. It is believed that the drift observed in both cases is due to sensors that are not loaded reporting a value. Since the pressure reported is the result of dividing the force recorded by the area of the insole activated, sensors reporting ghost values could significantly alter the pressure values reported. It is believed that the reduced drift experienced during the loaded phase of gait can be easily accounted for. Since more sensors are loaded during the stance phase, the percentage of senors that are reporting ghost values (instead of a zero value) is reduced, simply because less are actually experiencing zero load. Past papers have suggested that vaules below 35 kPa should not be recorded because these are below the recommended operating range of the sensors and a range in which they suffer from hysteresis. A hysteresis effect would result in the sensors reporting a pressure value when they are in fact unloaded. Thus, removing values recorded that are below 35 kPa was believed to be a possible solution to the drift observed in Figure 33.

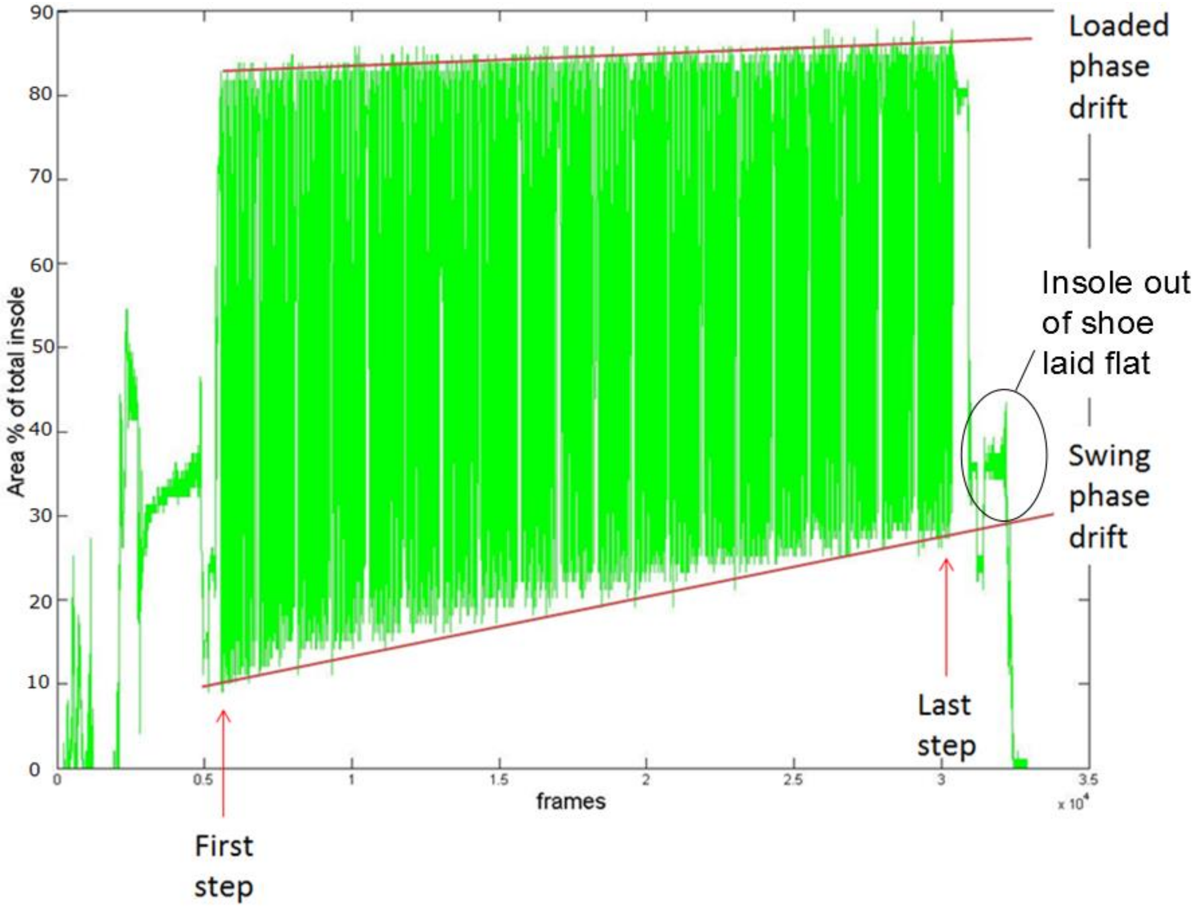

Figure 33: Drift in the raw area data

In Figure 34 we have a simular plot as Figure 33, however, sensors that record 35kPa or less have been removed. As can be clearly seen this completely removes the swing phase drift and any obvious signs of a drift in the loaded pahse.

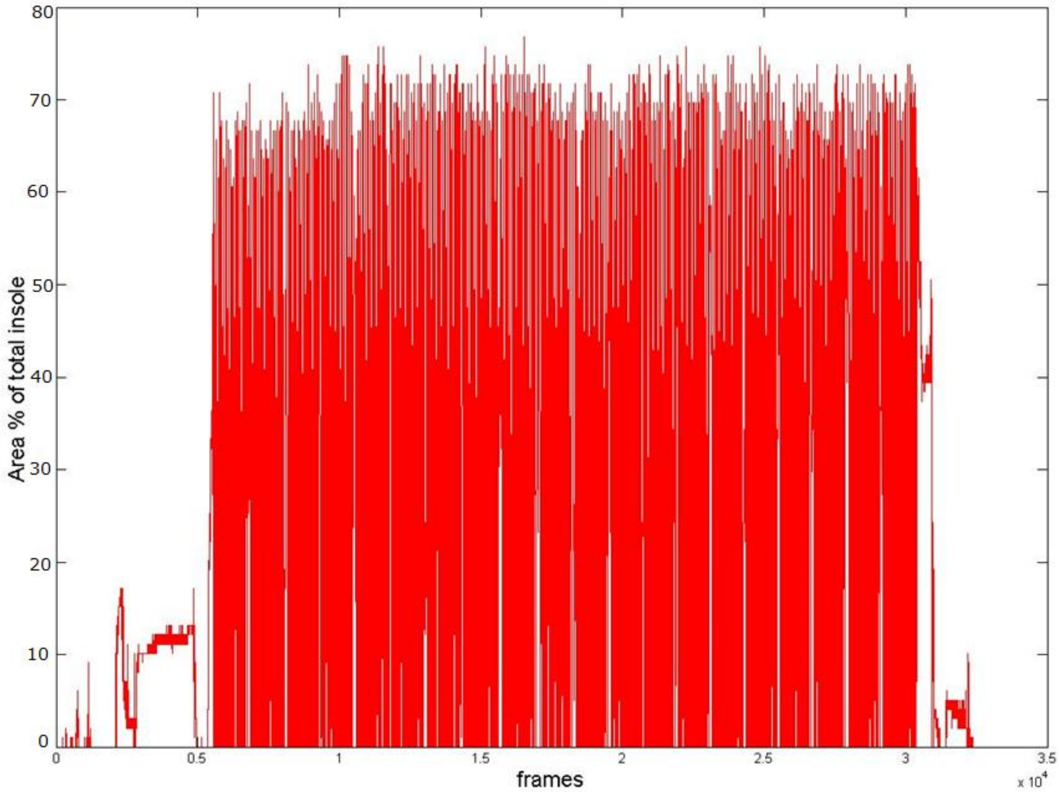

Figure 34: Plot showing the absence of drift in the filtered area data

From Figure 35 it is apparent that the total area of the insole that is activated is reduced by approximately 10 - 20% during both the loaded and unloaded phases. This will have a significant effect on the total load applied to all the sensors shown by force data as shown in Figure 36.

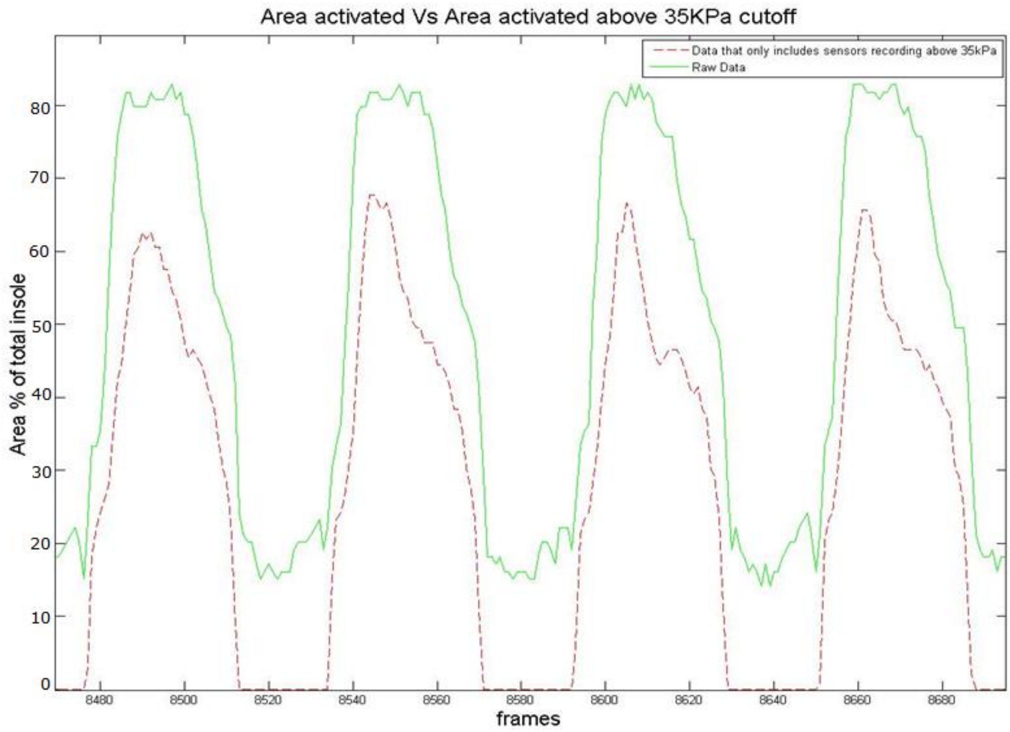

Figure 35: A comparison between raw and filtered area data, for four steps

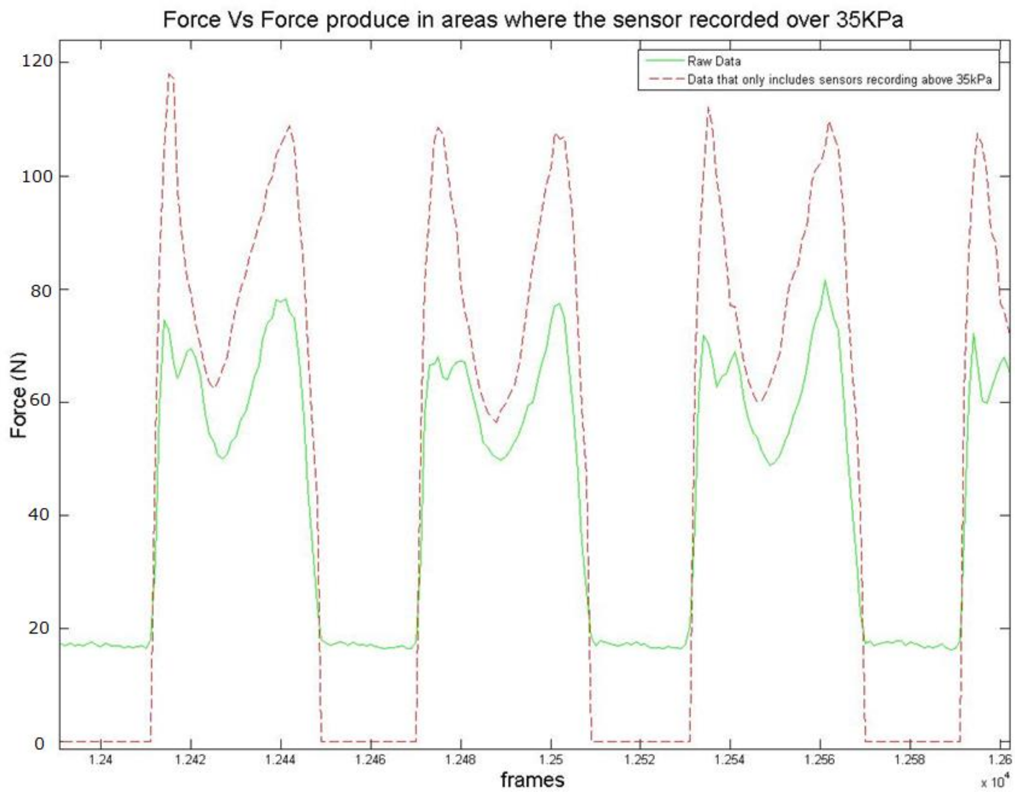

Figure 36: A comparison between raw and filtered force data, zoomed in to three random steps

Whilst the values of the removed sensors were low, in some cases the total number of sensors removed was numerous, as can be seen in Figure 35, where up to 20% of the insole had active sensors during swing before the sensors recording 35kPa were removed and close to 0% after the data had been removed. The result of removing these sensors slightly reduces the total pressure recorded, as can be seen in Figure 37, where a reduction of approximately 5kPa can be seen from the peak pressures recorded.

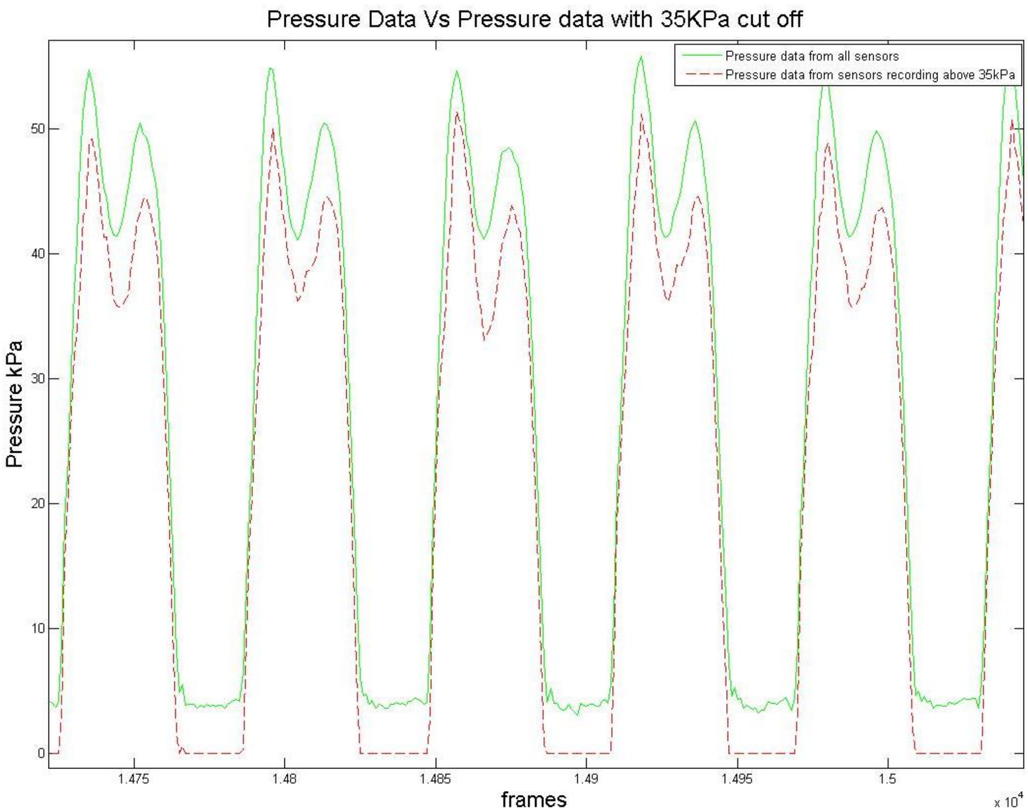

Figure 37: A comparison between raw and values below 35kPa removed, for five steps

Pilot Conclusion

From this test it was found that drift in the pressure recorded was present across the whole insole and this drift was also apparent in the force data, similar to the force drift that has been reported previously [169]. The primary cause of this was sensors recording values below 35kPa increasing the total area of the insole that was activated, and thereafter the force data being divided by an excessively high area value to provide the pressure recording. Discounting sensors that were below 35kPa, a value that below which it has been recommended should not be recorded [163] the drift in the force data is substantially reduced.

It is therefore recommended from these results that as much environmental acclimatisation as possible should be included in the protocol to warm and humidify the insoles. Whilst, an hour may not be possible, the period usually provided to enable the participant to acclimatise to the testing condition could also be used to acclimatise the insoles. After data collection values of 35kPa or less should be removed in order to remove the effect hysteresis of the sensors. The hysteresis effect can be most clearly seen by an increase in the unloaded force data, this is most apparent in **Figure 33** in the region marked 'Insole out of shoe laid flat', since the insole is completely unloaded during this period the value reported can only be due to hysteresis. Since the loading across all active sensors is divided to produce the final pressure value, removing sensors that are proving a false positive value make the final pressure value more accurate.

Timing gates

Two Brower tc-timing system light gates (Brower Timing Systems, Draper, Utah, USA) were used to measure walking speed over the 20m walking area. This enabled the researcher to provide verbal feedback to the participant so they could ensure they maintained the target speed (1.2 $m.s^{-1}$ ±5%) across the various footwear conditions.

As previously discussed, maintaining consistent walking speed is essential when collecting plantar pressure data so that valid comparisons are possible between experimental conditions. The purpose of this investigation was to find out how many steps the participant required to become acclimatised to the shoes and thus the same speed was required for all shoes. Therefore, a fixed speed was determined for all participants and conditions. From pilot investigations it was found that all women tested could walk in a range of high heels shoes at a walking speed of $1.2 m.s^{-1}$. Women were used because high heels provided the largest biomechanical perturbation to gait of all the shoes used in this test. To enable best comparison and enable the amalgamation of data it was decided that all participants should walk at this set speed.

3.3.3. Footwear

The footwear was chosen to represent a wide range of shoes that are commonly used for research, since researchers would be the main audience for the outcomes of this study. The shoes used are detailed in Table 3 and Table 4, and photographs are shown in Figure 38.

Females:

Table 3: Female shoes in the reliability study

Number	description
1	Decathlon Kalenji
2	55mm heel, softest upper
3	55 mm heel, stiffest upper
4	Duna 10° stiff rocker (Designed for people with diabetes)
5	Scholl starlit (rocker shoe)

Males:

Table 4: Male shoes in the reliability study

number	Description
1	Decathlon Kalenji
2	Duna 10° stiff rocker (Designed for people with diabetes)
3	Scholl starlit (rocker shoe)

Figure 38: The footwear used in the study
top left: 55mm heel; top right, Scholl starlit (rocker shoe); bottom left, Duna 10° stiff rocker; bottom right, Decathlon Kalenji

Both males and females wore the **Decathlon Kalenji** training shoe which represents the comfort sports shoe type, with a soft upper and a soft and flexible sole, heel cups and arch support. This shoe has been used in a range of biomechanics research [206-208].

The **Scholl starlit shoe** represents retail rocker or unstable footwear shoes, a category of footwear popularised by Masai Barefoot Technology (MBT) shoe, manufactured by the Swiss Masai company, Switzerland. The shoe sole is curved and designed to provide an unstable base of support in the anterior/posterior direction. It is also a complaint material and thus unstable in vertical and medial/lateral directions too. This footwear style has been shown to produce significant changes in the motion of the pelvis [195], hip [195], knee [195, 209], and ankle [195, 209] motion as well as plantar pressure [77]. The sole has a distinct anterior/posterior curved sole but the sole is compliant along its length. The footwear is thought to increase the activity of extrinsic foot muscles [210]. These shoe designs have been used for a range of objectives by different communities including: as a training tool [211], as a method of relieving the effects of degeneration of the calcaneal fat pad [168]; as well as many other foot and lower limb investigations [168, 212].

In contrast to the Scholl shoe, the **stiff rocker Duna shoe** (Duna, Maurice, Last: OMAR11, Structure: Standard Duna) has a sole that is very stiff in bending and compression and a distinct pivot point under the metatarsal heads, designed to enable the foot to rock forwards in propulsion. This design has been shown to move peak plantar pressure from forefoot regions considered high risk for people with diabetes [77].

For females, the **raised heel shoes** related directly to the work covered in the remainder of this thesis. They are not worn by the males because they are not commonly associated with male users and it is difficult to find males that have experience of walking in them, presenting a potential risk to the participant. Raised heel shoes have reduced base of support which increases instability at heel contact and most likely throughout stance. They also force the wearer to adapt their gait in a number of ways including: lower anterior pelvic tilt, lumbar lordosis, and sacral base angles [56], as well as the adapted hip, knee, and ankle motion during gait [69]. The position the foot has also been shown to induce the windlass effect, which subsequently stiffens the structure of the foot and raises the medial arch [24]. Since material stiffness relates to the fit and comfort of shoes it is relevant to the work presented later in this thesis. Two versions of the heeled shoe were therefore worn, with contrasting upper stiffness's to investigate whether this feature affected acclimatisation and the number of steps required to produce an average representative step.

3.3.4. Testing Procedure

Upon arrival the participant was given the opportunity to read the testing protocol, told what was expected of them and informed written consent was taken.

In order to enable the participant to familiarise themselves with the testing procedure and the required walking speed (1.2 $m.s^{-1}$ ±5%), they walked continuously along the length of the testing area for five minutes. During this period the Pedar insole was inside the shoes to enable measurement sensors to acclimatise to the environment inside a shoe.

Once the participant was able to consistently walk at the required speed, a complete dummy run of the test was completed. This was conducted whilst the participant was wearing their own shoe. The purpose of this was to ensure that the results were not affected by the participant requiring a period of time to become familiar with the testing procedure. Following this the rest of the shoes were tested in a random order which was generated by a MatLab script.

Before each trial the insoles were placed into the shoes and participants donned the shoes, adjusting lacing to suit their comfort. The Participants remained seated throughout and were not allowed to take any steps until instructed. They were then asked to walk the length of a 27m room. This distance comprised a 20m area in which data was collected (walking in a straight line) and a 3.5m space at either end, in which the participants accelerated/decelerated and turned around. The timing gates were positioned at the start and end of the 20m area so provided a measure of straight line walking (i.e. did not measure the acceleration/deceleration phase). In each shoe, participants walked continuously for 20 x 27m lengths, providing over 500 steps (250 on each foot). The assumption was that this period included both the acclimatisation period and a sufficient number of steps thereafter to achieve steady state walking. This process was repeated for each shoe until all the shoes had been tested.

3.4. Data processing and statistical analysis

3.4.1. The Pressure Mask used

In keeping with the majority of past research the foot was divided into regions. The purpose of using regions is to make the data produced by the 99 sensors in each insole more manageable, and to make changes in pressure more apparent. However, the simplest method is to compare the fewest regions but this means much of the information collected is lost [164-166]. A compromise therefore must be made between the ease of comparing few regions against the loss of data that this entails. Whilst, many papers report the masks used (Table 5) few report why the mask was chosen, two exceptions being Chapman et al, 2013 [77] and Li ping Wang et al, 2005 [182]. Past research has shown that there are regions of the foot that show similar or related pressure characteristics via use of a Harris mat and thus they recommended objective regions that could be studied [213]. However, the values provided by Bontrager et al [213], do not coincide with the boundaries of the Pedar sensors and therefore Chapman et al used the values as a guide and provided us with a new set of masks [77, 114], unfortunately without the use of a midfoot mask. High heel investigation have often reported findings of the midfoot [91, 181] and therefore it was concluded that the present study should also include the midfoot region. The added midfoot region therefore was produced using the sensors 27 to 54 of the Pedar insole, the final mask design can be seen in Figure 39 , and includes the following masked regions (masks): 1st metatarsophalangeal joint (MTP1),2nd–4th metatarsophalangeal joints MT24, the hallux, 5th metatarsophalangeal (joint MT5), the heel, and the midfoot.

Table 5: The foot regions used by previous high heel in-shoe, plantar pressure investigations.

Author	year	reference	regions	Regions used
Meir Nyska, M.D.	1996	[91]	7	Heel, Midfoot, lateral forefoot, medial forefoot, middle forefoot, lateral toes, hallux
Lan-Yurm Guo	2012	[181]	8	Heel, lateral midfoot, medial midfoot, central forefoot, lateral forefoot, hallux, toes, medial forefoot
Snow	2005	[105]	5	Hallux, metatarsal head 1, metatarsal head 2, metatarsal head 3, metatarsal heads 4 and 5
Caroline	2005	[24]	7	Heel, midfoot, lateral forefoot, central forefoot, medial forefoot, hallux, toes 2-5
Lee yung-hui	2005	[9]	5	Medial forefoot, hallux, lateral forefoot, midfoot, heel
Wei-Hsien Hong	2005	[109]	6	Hallux, toes, medial forefoot, lateral forefoot, midfoot, heel
Ming Rong	2009	[214]	7	Great toe, lateral toes, medial met heads, middle met heads, lateral met heads, middle foot, heel
Li Ping Wang	2005	[182]	8	Great toe, other toes, medial metatarsal head, middle metatarsal head, lateral metatarsal heads, medial arch, lateral arch, heel
Jung Ji-Yong	2012	[215]	3	Forefoot, midfoot, rearfoot

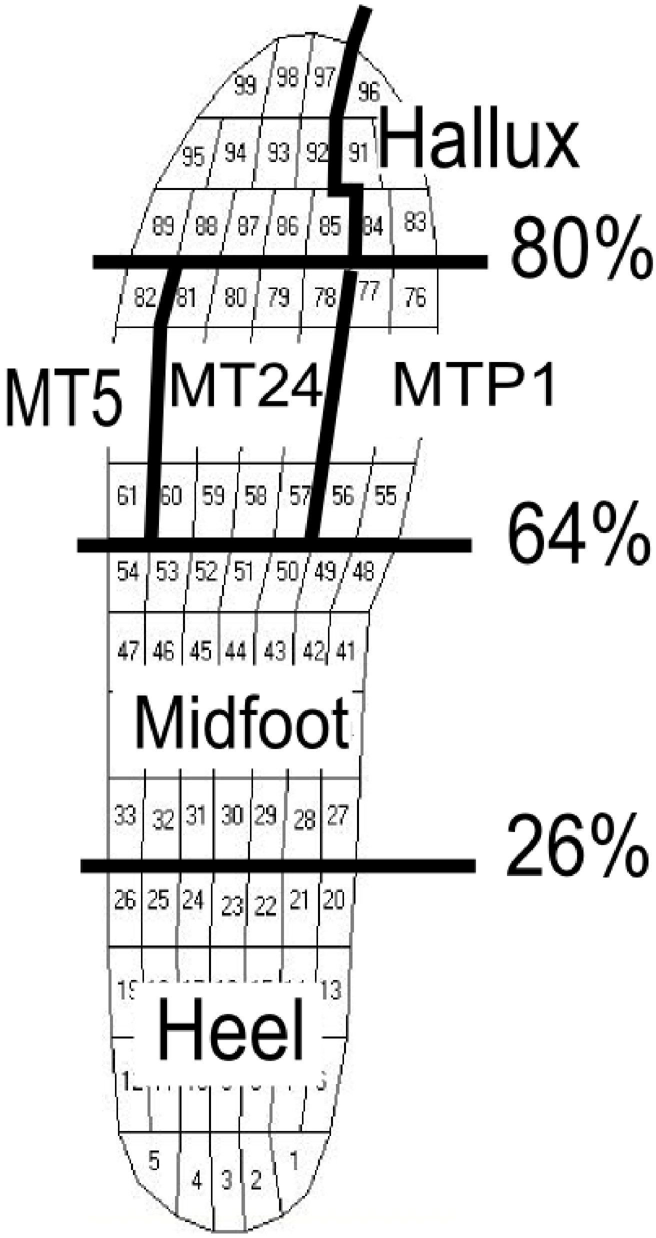

Figure 39: Pedar sensor groupings for the regional masks

3.4.2. Pre-processing

The data recorded during the acceleration, deceleration, and turning phases was removed to prevent them corrupting the data, this is consistent with past studies on diabetic footwear which used the same equipment [26]. To remove steps taken during acceleration and deceleration stages and turning at the end of the 27m length, steps with distinctly reduced peak values were removed (using a Matlab script). These were easily identified since they occurred in a regular pattern corresponding to the 27m length and in cases where there was doubt the step was removed.

3.4.3 Identifying the minimum number of steps required

It has been reported that the plantar pressure parameters; peak, mean and impulse can be compared both across studies and parameters [177], so comparisons can be drawn between studies that report any of these. As a result it has been suggested that using a smaller set of parameters is more effective at capturing the biomechanical behaviour being observed [177]. Peak pressure and pressure time integral have both been shown to correlate with comfort [183]. Peak pressure continues to be widely studied in a large variety of studies, thus developments in methods of improving protocols for peak pressure investigations is likely to be of more use than other parameters. Peak pressure was therefore chosen as the parameter to be investigated.

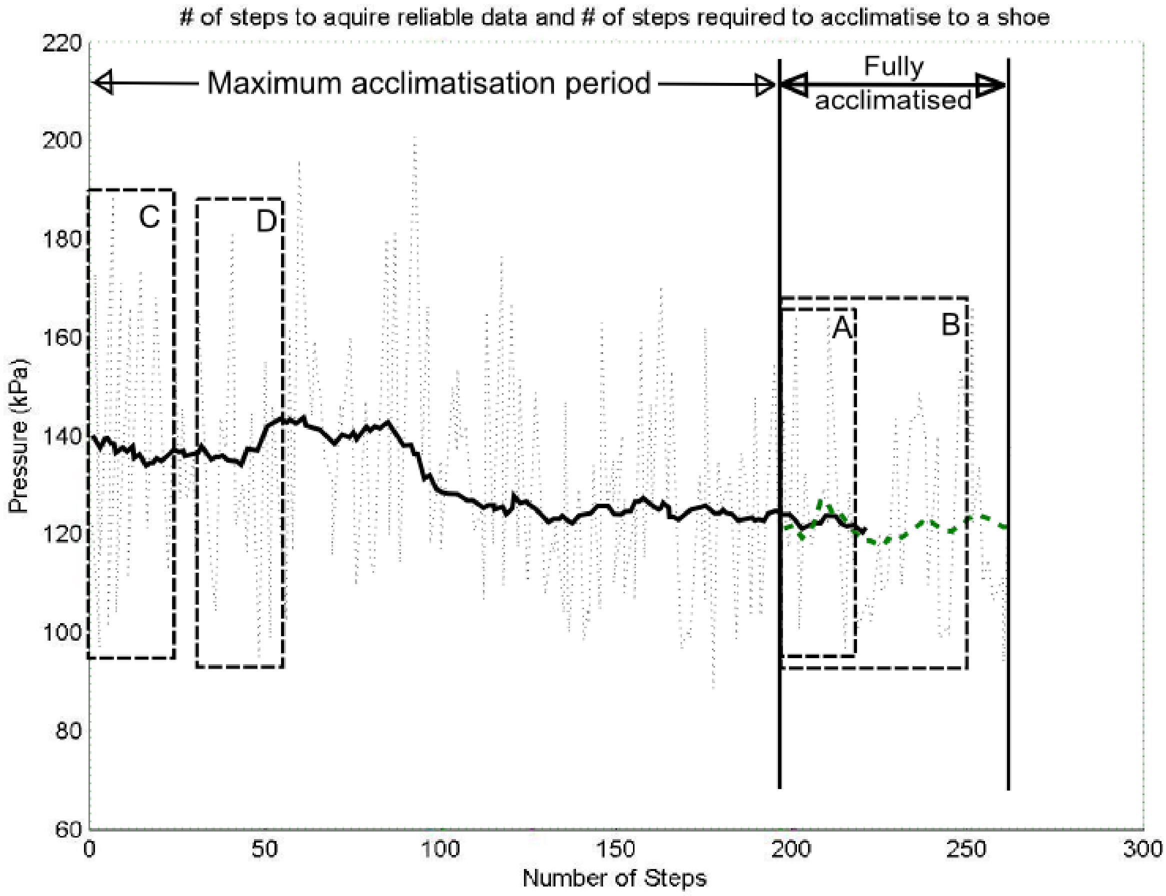

Figure 40: A depiction of the algorithms used to calculate the acclimatisation period and the number of steps required to produce an average representative step.

In order to address the two research objectives, it was necessary to make a number of assumptions. The first was that a maximum of 200 steps would always be sufficient for a participant to acclimatise to an unfamiliar shoe condition. This figure was chosen because it was suggested by Owings & Grabiner [187] and because it was in excess of the vast majority of protocols used in the literature. The second assumption was that, following acclimatisation, no more than 60 steps would be required to calculate an average representative step. This value is ten more than previous research has indicated is necessary [187] and far more than most plantar pressure studies. Pilot testing showed that 400m of walking was sufficient for participant to take at least 260 steps per foot, 200 to ensure acclimatisation and a further 60 from which an average representative step could be calculated.

A visual representation of how the data collected was used is shown in Figure 40 (raw data is the finely dashed line). The last 60 steps of the raw data are cumulatively averaged to produce P_{target} (thick green dash). As a visual aide Box A is used to show the window used to calculate the cumulative mean (P_{win}), Box B shows the same window but for later in the process and therefore includes more steps. It is this cumulative window that is used to find the number of steps required to produce a representative average step. Box C is used to identify the period required to acclimatise. This window is also used to calculate the mean over 30 steps. By moving Box C along the raw data line and plotting the resultant mean peak pressure is calculated, plotted as the thick black line). Box D shows the same as C but finds the mean peak pressure for a later step.

Finding number of steps required for valid data:

The first stage of the analysis was to identify minimum number of steps which must be averaged together to accurately represent normal gait following acclimatisation. This was achieved by comparing the peak pressure, averaged across the final 60 steps (P_{target}) with the peak pressure averaged across a window spanning a smaller number of steps (P_{win}). The width of P_{win} was gradually increased until the absolute difference between P_{target} and P_{win} was within a tolerance of 2.5%. This tolerance then had to be exceeded for five consecutive steps (to ensure stability) before the size of the window was taken as the minimum number of steps required for a representation of normal gait. The final value reported was the first of the five consecutive steps to meet the criteria. This idea is illustrated in Figure 1 which shows the target pressure P_{target} and two example windows of different widths (A and B).

The processed described above was repeated for each participant, each shoe and each anatomical foot region. A mean (SD) number of steps was then obtained for each region and shoe across all the participants and the final recommendation calculated as the mean plus 2 SD across all participants. From these data a recommended minimum number of steps, or window size (W_{final}), was then identified and this was used in the subsequent analysis (described below).

Finding the Acclimatisation period

To find the number of steps required for valid data, a cumulative average was used on the same data that was used to find the average of 60 steps. Due to this, the cumulative average and the 60 step average would eventually be the same value. It was therefore possible to use a very tight constraint of 2.5% difference between the cumulative average and the 60 step average before the result was accepted. For Acclimatisation, however, the window of observation was of a fixed size (30 steps) and different data was used for the 60 step average compared to that being observed for acclimatisation. This meant that it was possible the criteria may never be met if the limits were too tight, whilst if too loosely defined they may report a false result. To ensure a value was used that fulfilled the requirements, a range of values were used and the results studied. The results of the two of these tests, that of a 5% and 2.5% cut offs are shown in Figure 41.

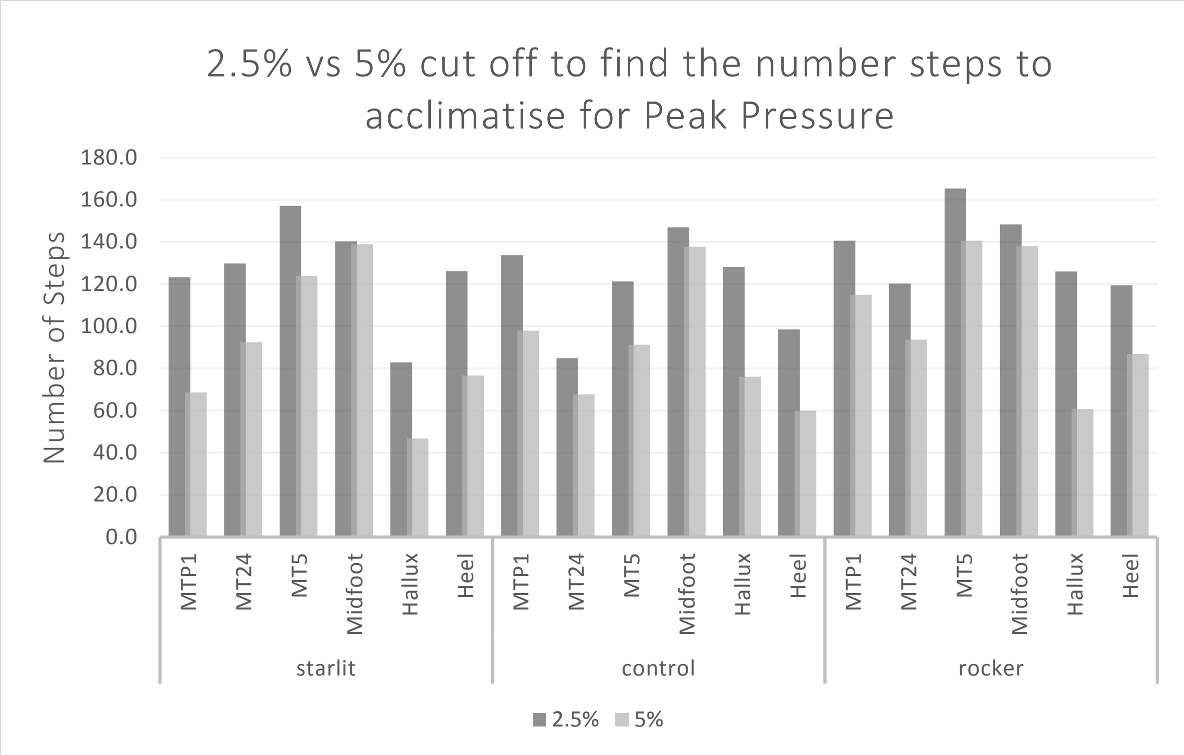

Figure 41: The results for the number of steps required to acclimatise for 2.5 and 5% cut off from the average representative step established earlier, using peak pressure.

As can be seen from Figure 41 the 2.5% and 5% plots follow a very similar pattern and as you would expect the 5% requires less steps than 2.5%. The two sets of plots following similar patterns implies that the data is stabilising and both 5% or 2.5% cut off could be used to define the end of the acclimatisation period. However, pressure data can be extremely variable and therefore enforcing the strictest requirements on data collection methodology means the most reliable results are reported in later studies. It was therefore decided that using 2.5% cut would be best.

To identify the number of steps required for participants to acclimatise to different footwear types, a window of width W_{final} was gradually moved in increments of 1 step along the peak pressure data (Figure 40). Note that Figure 40 shows two example windows at different positions (C and D). For each window position, average peak pressure was calculated across the window and compared to the target pressure (P_{target}) defined from the average of the final 60 steps (see above). Once the average peak pressure of the window was within 2.5% of P_{target} it was assumed that the participant had fully acclimatised to the footwear. The number of steps preceding the start of the window was taken to be the end of the acclimatisation period. This process was repeated for each participant, each footwear condition and each region, each time using a window of width W_{final}. A final recommendation for each footwear condition and region was then calculated as the mean plus 2SD across all participants.

3.5. Results

3.5.1. Minimum number of steps required for valid plantar pressure data.

In females the highest minimum number of steps was 39 (MT5, soft upper heeled shoe) Table 6, lowest was 14 (hallux, Starlit and Rocker). In males, the highest minimum number of steps required to provide representative peak PP data was 34 (midfoot, Starlit shoe), the lowest was 2 (Hallux, Kalenji shoe). When considering both genders the foot area requiring the highest minimum number of steps was MT1 (28 steps, based both on shoes common to male and females) and the area requiring the least steps was MT24 (13 steps). The difference between the shoe requiring the highest and lowest minimum number of steps (averaged across all foot areas listed in table 1) was just 5 steps for the male shoes, and 13 steps for the female shoes.

Table 6: Minimum number of steps required for reliable data.
The value two standard deviations above the mean is presented

Shoes	Gender	MTP1	MT24	MT5	Midfoot	Hallux	Heel	Average
starlit	both	29	12	24	28	18	18	22
Kalenji	both	30	15	29	24	12	28	23
rocker	both	26	13	25	26	12	27	22
Average	both	28	13	26	26	14	24	22
starlit	male	33	11	24	34	21	15	23
Kalenji	male	27	13	34	16	2	33	21
rocker	male	22	11	23	25	9	29	20
Stiff	*female*	*29*	*14*	*36*	*27*	*22*	*21*	*25*
Soft	*female*	*24*	*17*	*39*	*22*	*25*	*28*	*26*
Starlit	*female*	*26*	*14*	*25*	*22*	*14*	*20*	*20*
Kalenji	*female*	*34*	*16*	*23*	*29*	*16*	*23*	*23*
Rocker	*female*	*31*	*15*	*28*	*28*	*14*	*27*	*24*

3.5.2. Minimum number of steps to complete the acclimatisation period

The following tables show the data on the acclimatisation period when the threshold used is 2.5% from P_{target} as per the recommendations above. All values in the table are two standard deviations above the mean to ensure robustness and the sliding window used was dependent on the shoe and foot region used.

Table 7: Acclimatisation period (number of steps)
using windows that are foot region and shoe dependent (female)

Shoes	MTP1	MT24	MT5	Midfoot	Hallux	Heel	Average
Stiff	117	132	143	141	105	114	*125*
Soft	104	79	135	123	149	93	*114*
Starlit	136	145	168	115	95	113	*129*
Kalenji	156	87	133	176	142	67	*127*
Rocker	138	152	153	154	116	156	*145*

Table 8: Acclimatisation period (number of steps)
using windows that are that are foot region and shoe dependent (male)

Shoes	MTP1	MT24	MT5	Midfoot	Hallux	Heel	Average
Starlit	114	121	152	167	74	145	129
Kalenji	114	88	110	121	114	123	112
Rocker	128	87	148	139	140	56	116

With a window of observation that represented the number of steps required to produce an average representative step that was individual for the mask and the shoe, the longest acclimatisation period was 175 (females) and 167 (males). These were observed in the Midfoot region of the Kalenji shoe (female) and the midfoot region of the starlit rocker shoe (male). Whilst this shows that both the shoe used and the foot region influence the acclimatisation period, in reality a participant cannot walk a different number of steps for each foot region, the remaining comparisons will only have a set window size for all conditions to enable comparison. In the discussion of this chapter a 30 step window will be recommended, due to the results previously presented and therefore will be used herein.

Based on the shoes common to both males and females, the longest acclimatisation period was 166 steps (MT5, Rocker shoe) and the shortest was 83 (midfoot, starlit). For the females, the longest acclimatisation period was 175 steps (midfoot, Kalenji shoe), shortest was 67 steps (Heel, Kalenji shoe). For the males, the longest acclimatisation period was 167 steps (midfoot, starlit shoe) and the shortest 56 steps (Heel, rocker shoe).

Table 9: The number of steps required to acclimatise to footwear using a 30 step window with data from both genders combined, the value two standard deviations above the mean is presented

Shoes	Gender	MTP1	MT24	MT5	Midfoot	Hallux	Heel	Average
Starlit	Both	124	130	158	141	83	127	127
Kalenji	Both	134	85	122	147	129	99	119
Rocker	Both	141	121	166	149	127	120	137
Average	Both	133	112	148	146	113	115	128

The foot area with the longest acclimatisation period was the MT5 (166 steps, based on male and female combined data), and the hallux had the shortest period (83 steps). The shoe with the longest acclimatisation period was the rocker shoe for females (145 steps averaged across all foot areas) and Starlit shoe for males (129 steps). The shoe with the shortest acclimatisation period was the soft upper heeled shoe for females (114 steps) and Kalenji shoe (112 steps) for the males.

3.6. Discussion

3.6.1 Introduction

There were two aims to this study:

1. To investigate the number of steps required to produce an average step that is representative of normal gait
2. To investigate the number of steps required for a participant to acclimatise to a range of footwear types.

These objectives were to be completed with plantar pressure data as the method of observation. A range of footwear was used to represent the variety of challenges a participant may be expected to become acclimatised to in a research environment. The data was divided into foot regions to aid comparison with past research and to provide the most useful data for future research.

A new approach was implemented to determine the minimum number of steps over which plantar pressure data should be recorded to provide valid peak plantar pressure data, i.e. data that is representative of the real pressure experienced during walking. Furthermore, a novel approach to establish the number of steps required to acclimatise to unfamiliar footwear was implemented. Data from both genders was combined and showed that the maximum number of steps required to produce a step representative of an average step is 30 and the maximum acclimatisation period is 166 steps. However, these two maximal requirements were not for all footwear conditions or all the foot regions for the same footwear condition. It therefore, stands to reason that the number of steps required may be less if the focus is on just one shoe or region. This result would be of particular interest to investigations that are focused on just one foot region as there was little change between shoe conditions. It should also be noted that these values where intentionally chosen to represent the upper boundaries of what is required and therefore the mean value plus two standard deviations were derived to form these recommendations providing values that includes 95% of participants.

According to the data and the assumptions made, the minimum number of steps required to produce an average step was 30. This is greater than the 12 steps suggested previously however this suggestion was based on study of the foot affected by diabetes and neuropathy [26]. As previously explained this may be because gait of those with diabetes is often slower and less variable than healthy individuals. Added to this, the prior study only used a 20 step protocol and thus could only have found that less than 20 steps are required due to the convergence of their data. Furthermore, Of all the investigations found that document the number of steps saved during testing [24, 109, 141, 145, 182, 183, 216] only Wang and li 2005 recorded a sufficient number of steps [182].

The regions with the least variability and thus required the least steps to produce an average step, for both genders, was the MT2-4 followed by the hallux. These two regions represent those where high pressures are often reported [24, 91, 181, 182, 217], they are also loaded in the later stages of the loading cycle. The high loads mean that small changes in the loading are less significant, and the late phase in the gait cycle provides the foot with more time to adapt to any variability in the contact phase resultant from the natural variability in gait such as stride length or width [187]. Subsequently the need for areas in the forefoot to adjust their loading may be reduced relative to that of the rear foot. This would lead to greater consistency in the pressure values and therefore fewer footsteps would need to be measured.

There seems to be little effect due to the footwear designs and thus it is concluded that the number of steps required to produce valid plantar pressure data is not strongly dependent on the footwear. This is surprising given the varied design chosen, but it perhaps reflects the ability of the foot to quickly accommodate new positions or external constraints, and thus settle into a steady state in terms of plantar loading.

According to the data and the assumptions made, to acclimatise to an unfamiliar pair of shoes 166 steps were required. Males required fewer steps than females. For both genders it is the MTP5 and midfoot that requires the most steps to acclimatise. Males acclimatised quickest in the Kalenji shoe, most likely because these are similar to designs regularly worn by these participants. The Starlit required the most steps in males, unsurprising given that this shoe was designed to create a significantly different and so called “unstable” interface [218] that none of the participants had prior experience of. By contrast, in females the Kalenji shoe required the most steps to acclimatise whilst the stiff high heel required the least. Further investigations need to take place to better understand why this is the case. However, one explanation is that the higher pressures generated by the high heeled type footwear mean that small variations in pressure are less significant.

An important issue is whether prior research meets the recommendations proposed in this study. The few papers that have reported an acclimatisation period for each footwear condition all provided sufficient opportunity for acclimatisation according to these results [24, 109, 141, 145]. However, the recommendation for 30 steps for valid data is greater than in many studies [24, 109, 141, 145, 182, 183, 216]. Indeed, only Wang and li recorded a sufficient number of steps (30 steps collected with a ten minute break between conditions) [182]. However, it is true that in some studies it may not be realistic to ask participants to perform 30 steps. For example, in cases of sensory neuropathy and diabetes, it might expose participants to risk if they are asked to walk too many steps in too many shoe conditions. However, arguably, the solution is to reduce the number of shoes in order to have better quality data.

3.7. Limitations

3.7.1 Study design

This study has several limitations.

1. The assumption that 200 steps were more than necessary to acclimatise and that 60 steps were sufficient to acquire valid data are limitations. However, they are based on the findings of past research and represent assumptions that are commonly made in footwear and gait investigations. Whilst it could be argued that much longer periods are required to distinguish a macro gait cyclic pattern, doing this would not represent a useful and viable method of collecting data in future studies.
2. Only healthy participants rather than those affected by disease, which might alter step to step variability and change the recommendations, were included in this study. However, the purpose of this study was to provide the most useful data possible to provide a base line for the majority of investigations. To increase this, the upper second standard deviation was used to widen the included population.

3. The results are based on anatomical masks which can lead to a loss of data. To avoid this statistical mapping could be used [166], however, this is still not widely used in research investigations, thus limiting the usefulness of the results and making difficult to drew comparisons to past results.
4. The tests were conducted in a research lab and because of this the trials did not consist of 400m of continuous walking, instead the participant walked lengths of the room until they had completed 400m. The steps taken during the turning phases were subsequently removed. However, it is rear that in any situation test or real world that a person will walk 400m without any deviation in direction
5. The speed used in this investigation was chosen so that all participants would be able to complete the study in all footwear. This speed is unlikely to have been the normal walking speed of all the participants and therefore may have increased the viability of the walking trial. Control of the walking speed is an essential part of a plantar pressure investigation and therefore all studies that investigate this type of data have to overcome the same limitation.

3.7.2. Equipment

Whilst attempts were made to reduce the effects of sensor drift, the sensors do still show some level of variability. Much of this can be attributed to the hysteresis and offset temperature drift which have been reported by Pedar to be <7% and <0.5 respectively. Also over the course of their life span, sensors and wires become damaged potentially affecting the data.

3.8. Conclusion

This study has shown that whilst past research has acknowledged the need for an acclimatisation period by including them in the study [24, 141, 145], few had accurately determined the correct period required. Whilst wearing a diabetic rocker shoe past research has suggested that recording twelve steps is sufficient for valid data [26], this is not in agreement with the current study. If all foot regions are required then it is recommended that the period given for acclimatisation is greater than 166 steps per foot. Following this, in order to ensure the quality of the results presented, it is recommended that at least 30 steps are recorded. However, it may be possible to reduce this figure by selecting foot regions or footwear that has reduced variability during gait.

In summary, it is recommended that the period required to acclimatise to unfamiliar footwear is 166 steps per foot and that to obtain valid data no fewer than 30 steps of plantar pressure data should be recorded. The latter recommendation is not met by most studies in the literature.

Chapter 4: An Investigation into the Effects of Heel Height and Upper Stiffness on Comfort and Pressure

Chapter 4 Introductory outline:

The focus of this chapter is the effects of heel height and upper material stiffness on pressure and comfort. In addition, the work in this chapter also investigates the effects of fit and lacing on pressure and comfort. To ensure the quality of the data there is a review of comfort questionnaires and an appropriate questionnaire is chosen for the use of high heel comfort comparison

The experimental study in this chapter investigates whether comfort and plantar pressure are affected by changes in heel height and upper material stiffness. The aim is to identify the effects of incrementally changing heel height and whether these effects are altered by a change in upper stiffness.

4.1. Introduction:

A high heeled shoe is easily identifiable due to its large heel piece, which raises the heel of the foot higher than the forefoot. The raised heel is the primary reason for the increased plantar pressure experienced by the wearer's forefoot [39, 72]. High heeled shoes are common in a large range of upper types and heel designs, each of which has a potentially different effect on the wearer. A more detailed definition of a high heel and its variations were discussed in chapter 2.

It has long been reported that comfort is reduced when wearing higher heeled shoes [9]. Comfort is a complex and subjective quantity that combines physical information from foot nerve receptors (e.g. pressure, pain, temperature) with person specific experiences and perceptions.

It has been shown that footwear with greater comfort will have a lower injury rate [132]. It has also been shown that shoe comfort should be one of the primary concerns of footwear manufacturers because a potential buyer can quickly identify a comfortable shoe [21, 219, 220]. It is then essential for both the health of the wearer and the sales of the company that shoes are designed to optimise comfort. Despite comfort of high heeled shoes having been investigated before, current understanding of how to improve the comfort of a high heeled shoe is still somewhat limited. This lack of knowledge is in part due to the many possible shoe features, and variations of each feature, that might impact upon comfort. Furthermore, past research has often failed to control variables between different shoes being tested and therefore there are multiple independent variables being tested. Thus, any change in comfort cannot be attributed to any specific footwear feature. Some studies have compared shoes of visibly different types, such as high heels and sneakers [39] thus rendering it near impossible to attribute a given effect to a specific feature of either shoe type. Such studies can show whether there is a difference in comfort between shoes but not explain why the difference occurs. This is of little value to footwear designers.

It has been shown that raising the height of a shoe heel increases the pressure under the plantar surface of the forefoot [10, 23, 39, 42, 44]. Despite this there is not a clear method of predicting how much the pressure will increase if the heel is raised by a predefined amount. It is, therefore, difficult to build a systematic understanding of the effects of this apparently critical shoe feature on pressure and comfort. This is important because most shoes have some heel and 'high heels' remain a very popular consumer choice and therefore business opportunity.

Chapter 2 contributes to a detailed explanation of what we currently know about the effects of raising the heel of a shoe. To summarise: increased heel height plantarflexs the foot which reduces its functional length and makes the foot a more rigid structure. The result of this is that the forefoot carries more load [11, 23, 92] and the heel less [23, 25] during normal walking. The increased pressure at the forefoot is focused on the medial side, resulting in a reduction in pressure at the lateral side [23, 25, 39, 42, 53, 65]. The vertical and anteroposterior ground reaction forces also increase [25, 27, 43, 51], there is an increased impact force [42], reduced time to maximum pressure [44], and higher force-time and pressure-time integrals at the medial forefoot [23].

As previously outlined in chapter 2, there are varied definitions of a high heel. It was necessary for the purpose of this thesis to outline a definition that related not only to the shoe but also to the foot. This would help translation of the research to both shoe designers and those interested in foot health. To achieve this the effective heel height [24] definition has been adopted. The Effective heel height is the difference between the vertical position of the base of the heel pad (foot) and the sole of the foot at the forefoot (under the metatarsal heads).

Whilst it is known that the choice of upper can affect the comfort of a shoe [89], it is not known what property of the upper has this effect. It could be the shape of the upper, the volume it creates for the foot inside the shoe, or the material properties of the upper itself that affect pressure and comfort. If it were any of these the properties, then that particular property could be adjusted to negate the increase in plantar pressure, observed under the forefoot due to use of higher heels. This could enable an aesthetically pleasing shoe to be designed (i.e. heel height increased) whilst protecting the wearer from potentially damaging plantar loads, and promote comfort. However, the independent effects of these features have yet to be investigated across a range of incremental heel heights. Perhaps the only exception to this void in current understanding is the evidence relating to the effects of heel wedge angles and heel seat length. However, the findings showing that optimal heel seat length changes with different heel heights is evidence of the interaction between the effects of footwear features [36]. Thus, it is not sufficient to only know how each footwear feature affects pressure and comfort because how the combination of features have an effect is evidently also important.

Without knowing how features such as upper properties affect plantar pressure and how any affect interacts with the effects of changes in heel height, a shoe designer has no means of adjusting the upper shape, volume or material properties to try and compensate for the known effects of increases in heel height. Design cannot therefore be driven by research informed knowledge.

The stiffness of a high heeled shoe upper has been implicated as risk factor for reduced foot health when wearing high heeled shoes [79]. It is clear that a shoe that is too tight is undesirable from comfort and health perspectives [4, 44]. However, an upper of a high heeled shoe that does not sufficiently grip the foot will be unable to prevent the foot sliding inside the shoe. This may result in the toes being compressed against the toe box [79] or the shoe coming off the foot. It is also unclear if the fit of a shoe upper (i.e. its geometry compared to that of the foot) needs to be adjusted depending upon the stiffness of the material used for the upper. Whilst a more flexible upper material may reduce compression of the forefoot, which may reduce plantar pressures and improve shoe comfort, it may also allow the forefoot volume to increase 'too much'. Such a shoe would in effect act like a much wider shoe with a stiffer upper and the shoe may no longer be a good fit for the wearer.

The aim of this chapter is therefore to investigate how systematic changes in heel height affect plantar pressures and comfort and, how the stiffness of the shoe upper affects this relationship. The purpose is to improve current understanding of, if and how changes in upper materials might be used to offset the assumed increased pressure under the forefoot as heel height is increased.

4.1.1. Measuring shoe comfort

Pain (or discomfort) and comfort can be considered opposing sensations that are felt on the same scale. A lack of pain stimulus from the body's peripheral sensory system might therefore be defined as evidence of "comfort" [221, 222] though this ignores the fact these perceptions lie on a continuum. Due to the relationship between pain and comfort, footwear studies that have investigated comfort have taken inspiration from pain studies, with some authors clearly outlining how pain studies have influenced their investigations into footwear comfort [219]. It follows that measurement of comfort has much in common with measurement of pain. Those that have investigated footwear comfort have primarily used five methods to quantify the shoes:

1. A Borg CR-10 [223],
2. A Likert Scale [221],
3. 15 point ranking scales (extended Likert Scale) [197, 224],
4. A Visual Analogue Scale (VAS) [219, 225],
5. Asking participants to rank the shoes relative to each other [183].

The Borg scale is named after its creator Borg [226], whist the suffix CR stands for 'category scale with ratio properties' and finally the numeral 10 tells us the number of categories there were. The Borg CR-10, Likert, and the 15 point rating scale all follow a similar concept, in that they provide the participant with a list of anchor words which describe different perceptions of comfort. These words, called categories, are listed in order often from the least comfortable to the most comfortable, allowing the researcher to prescribe each category with a numerical value to aid analysis. A comparison of the Borg, Likert and VAS approaches to assess exercise related symptoms identified the VAS as the most reproducible over 5 consecutive days [227]. However, the methods have different sensitivity to different phenomena, with the VAS most sensitive to breathlessness and the Borg most sensitive to general fatigue [228]. In footwear specific investigations there have been comparisons between VAS and Likert Scales which have shown that both are reliable [229], the same study found that there was no significant difference between trials when using a VAS but there were when using a Likert Scale. A further study has shown a VAS was the most repeatable across all trials [227].

Asking participants to rank shoes relative to each other is a robust method of comparison within a study to identify a prioritised list of preferred footwear. Despite being robust the results when using this method are limited in terms of how data from different studies are synthesised. Since, every study would need at least one shoe from a prior study to enable comfort of shoes from a range of studies to be compared. A further limitation of this approach is, too many comparisons may lead to the participant becoming confused. Also, differences between footwear may be quite marginal, and the participant may become fatigued by the volume of questions and thereafter may resort to guessing.

The design of a VAS can affect the quality of the data. In particular the choice of anchor words is imperative as a floor effect has been observed [230]. A floor or ceiling effect in such scales, is when the range provided is inadequately wide and as a result grouping of data points occurs at the end of the scale. If a floor effect occurs then it becomes impossible to distinguish between results thus preventing the scale recording a change that does in fact occur. The length of the scale has been shown to be less essential, with 10 cm and 15 cm scale being interchangeable [231]. The orientation (vertical or horizontal) has also been shown to have no apparent influence [230]. However, it has been recommended that investigators reach a consensus on what type of VAS is used in similar studies [230]. Researchers measuring comfort of athletic footwear typically adopt the VAS developed by Mündermann et al [132, 219]. However, this approach has not transferred to evaluation of high heeled shoes. Indeed, even when the co-authors of Mündermann et al [219] published work on high heeled shoes, they used an alternative method of measuring comfort [66]. This clearly indicates some style specificity in the construction and context of a comfort measurement scale is needed. Indeed, the questions asked in Mündermann et al [219] are quite specific to a sport shoes and aimed at participants that have a greater understanding of shoe features, as athletes often do. On both these issues the tools might not be transferable to a non-athletic population.

4.1.2. Aims

There are six primary aims to this investigation:

1. To identify the effect of increased heel height on (A) plantar pressure distribution and (B) comfort
2. To identify the effects of increased upper material stiffness on (A) plantar pressure and (B) comfort

3. To investigate if an interaction exists between upper material stiffness and heel height by assessing the changes in (A) plantar pressure and (B) comfort.
4. To investigate whether the tightness of lacing can affect the outcomes of aims 1, 2 and 3.
5. To identify an appropriate method of investigating fit in the forefoot area (match between shoe shape and foot shape).
6. To investigate if the forefoot fit (match between shoe shape and foot shape) can affect the outcomes of aims 1, 2 and 3.

Based on the outcomes of the prior literature review, by addressing these aims the study will answer these hypotheses:

1. Pressure under the medial forefoot will increase with increased heel height
2. Pressure under the lateral forefoot will reduce with increased heel height
3. Comfort will reduce under the forefoot with increased heel height
4. Pressure will increase under the forefoot with increased material stiffness.
5. Comfort will reduce under the forefoot with increased material stiffness.
6. Comfort and pressure will be inversely correlated with each other.
7. An optimal upper material stiffness will exist for each heel height which provides the greatest comfort, thus demonstrating that there is an interaction between heel height and upper material stiffness.
8. An optimal upper material stiffness will exist for each heel height which reduces peak plantar pressure, thus demonstrating that there is an interaction between upper material stiffness and heel height.

4.2. Methodology

4.2.1. Participants

The participants for this study were recruited from the student and staff populations of the University of Salford. Recruitment was carried out via email and posters.

The inclusion criteria were:

- Females between the ages of 18 and 45
- Must be free from known lower limb injuries or abnormalities that affect their gait pattern
- Must free of health and neurological conditions that are known to affect gait such as diabetes and neuropathy.
- They must be able to walk unaided for 1.5 hours
- The participants must be able to understand both written and spoken English

4.2.2. Measurements

The experiments require measurement of:

1. Plantar pressure and comfort in shoes with a range of heel heights and uppers of varied stiffness's
2. The match between shoe and foot geometry.

<u>Measurement of comfort</u>

A *comfort questionnaire* was designed to evaluate how comfort changed with variation in shoe designs and to allow changes in comfort to be related to changes in plantar pressure. A review of the literature indicated that a questionnaire was required that was accessible to a non-expert user of footwear, but also had some elements common to Mündermann et al [219], which would facilitate comparisons between footwear categories. In addition, questions should focus on aspects of heeled shoe design that are specific to the footwear category and research questions posed (e.g. effects of forefoot volume of the shoe). The comfort questionnaire developed and implemented (

Figure 42) consisted of 150mm horizontal lines and asked 10 questions about specific aspects of the shoe. Where appropriate these were common to those used by Mündermann et al [219], although the language was changed to improve its usability.

The questions for overall comfort and shoe length were kept with similar wording, whilst the question on the forefoot was broken into toe and ball of the foot areas. Slight changes were made to the question on the arch of the foot where the term "height" was removed because it was felt that the height of the arch may not be the only reason for a change in pressure or comfort. Similar changes were made to the questions on forefoot and heel where the word "cushioning" was removed. The question asking for the comfort of the medial lateral control was removed as it was felt this would be confusing to those not familiar to footwear terminology. To further prevent confusing terminology the question on the heel cup was removed and instead questions were asked on the comfort of the heel sole and the back of the heel. Overall width and comfort of the top of the foot was also added in order to include all surfaces of the foot, which would mean that the region creating discomfort could always be identified.

The final design was preliminarily tested on 4 participants who fulfilled the inclusion criteria for the main study of this chapter. Once they had been shown how to complete that VAS the participants were asked to provide feedback on the VAS design to which none reported any problems or difficulties in completing it. Each participant completed the questionnaire 11 times, each time after wearing a different shoe including a control shoe that was repeated three times and a further 8 shoes. The whole test was repeated 4 times over two days. Between days the highest average change for a single participant was 2.3cm (±1.5) when wearing high heels, the average change for all participants whilst wearing high heels was 1.8cm (±1.3).

Shoe reference: .... participant:..

Comfort Scale

Please answer the following questions by placing a mark on the scale (**the horizontal line only**), indicating how strongly you agree to the comments.

How do you rate the Overall comfort of this shoe?

very comfortable ______________________________ Not comfortable

How do you rate Overall width comfort?

very comfortable ______________________________ Not comfortable

How do you rate Overall length comfort?

very comfortable ______________________________ Not comfortable

How do you rate the Comfort of sole surface, in the heel region?

very comfortable ______________________________ Not comfortable

How do you rate the Comfort of the back of the heel?

very comfortable ______________________________ Not comfortable

How do you rate the Comfort on top of the foot?

very comfortable ______________________________ Not comfortable

How do you rate the Comfort under the foot arch?

very comfortable ______________________________ Not comfortable

How do you rate the Comfort at ball of foot (sides)?

very comfortable ______________________________ Not comfortable

How do you rate the Comfort at ball of foot (sole)?

very comfortable ______________________________ Not comfortable

How do you rate the Comfort of toes?

very comfortable ______________________________ Not comfortable

Please shade any areas of particular discomfort or pain on the following images, mark one view per problem:

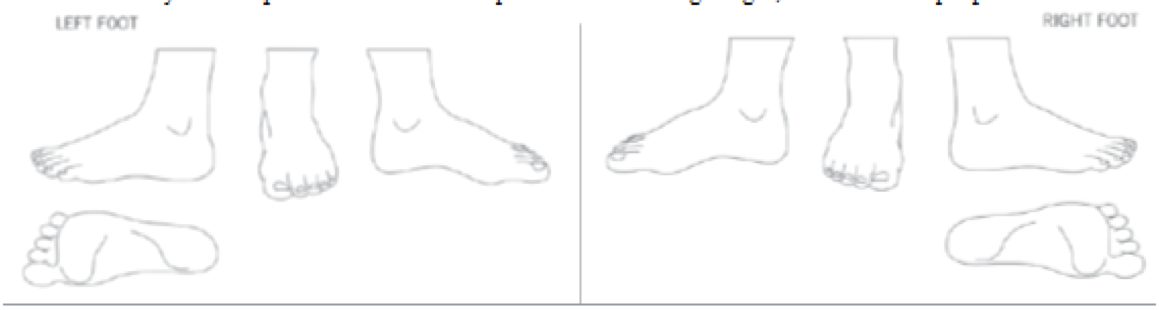

Figure 42: Comfort Questionnaire (not to scale)

Measurement of plantar pressure

Plantar pressure for the various shoe conditions was measured to understand how plantar pressure changes when heel height and upper stiffness change and how plantar pressure and comfort relate to each other. In-shoe plantar pressure was recorded using Pedar-X system (Novel GMbH, Munich, Germany). The insoles were placed in the shoes between the sock and shoe insert. The Pedar insoles were connected to the data logger that was attached to the participant via a waist belt. From the data logger the data was transmitted to a laptop computer wirelessly via Bluetooth. A more detailed description of Pedar was provided in chapter 2 and 3, including how best to collect data and when values should not be accepted due to the limitations of the system, these recommendations were adhered to throughout this investigation.

Measurement of foot and last shape

The 3D shape of the foot was measured to allow the relationship between it and the last (i.e. the internal shape of the shoe) shape to be quantified. Each participant had their foot shape measured using a 3D Foot Scanner (Icad PIE, INESCOP, Spain). The foot was placed flat on the glass platform within the scanner whilst the participant stood relaxed. The other foot was on an adjacent platform at the same height as the foot being scanned.

A 3D foot scanner (Icad PIE, INESCOP, Spain) provided 3D foot shape data. To do this the scanner emits a line of infra-red dot lasers which are subsequently detected by receivers. The time lag between light emission and the subsequent reception enables the device to perform a line of measurements on the foot surface. This process is repeated at 1 mm intervals along the foot. Once the scanner has traversed the length of the foot, all the measurements taken are represented as a point cloud. From the point cloud a mesh can be made from which measurements can be taken with the accompanying software. Once a foot scan is taken, the image is filtered to remove noise due to ambient light. Any further noise was removed manually on screen. The point cloud was then exported to Rhinoceros 3D software as a mesh (McNeel North America, Seattle, WA, USA), and the INFOHORMA (INESCOPE, Spain) plug-in software used to take specific foot shape measurements. These would later be compared to footwear last shape data collected using the same method.

There are some measurements that are believed to be good representation of foot shape and are commonly used in the foot health sector, such as navicular height which is also used as a predictor of arch height [232]. Despite this the scanner is unable to collect them. Many of these same measurements are also used by the scanner's software in order to orientate the foot. Therefore, in order to get the best results the manufacturer recommends the user takes these measurements by hand. These measurements include: Navicular height (distance between the navicular tuberousity (NT) and the ground), navicular width (distance between the NT and the foot midline (the foot's long axis), navicular distance; (distance between the NT and the pterion); big toe height; and big toe width.

Measure of shoe lacing

Shoe comfort may be affected by the preferred lacing tightness. This may vary between individuals and therefore it was decided that participants should lace their own shoes to their preferred tightness. As a result, the investigator did not know how tight the laces were, nor if the tightness was consistent across shoe conditions. However, maintaining the lacing in a consistent position could be important since it affects both upper position and potential slack in the material increasing the total volume available to the foot. In order to quantify tightness of the laces and ensure consistency between shoe conditions, a Vernier calliper (Silverline 380244 150mm Digital Vernier Caliper) was used to measure the distance between the top two rows of lace eyelets in each shoe condition. The difference between the participants could then be investigated.

Walking speed

Two Brower tc-timing system light gates (Brower Timing Systems, Draper, Utah, USA) were positioned 12m apart and used to measure walking speed. There was a further 3.5m before and after the timing gates to allow acceleration and deceleration areas either side of the area where measurements would occur.

4.2.3. Footwear designs investigated

The shoes used in this study comprised five different heel heights (35mm to 75mm in 10mm increments) and three different uppers. In increasing order of stiffness, as defined by the manufacturer, these were: goat suede (considered soft in the footwear sector), bovine suede, and bovine leather (considered stiff in the footwear sector). These were chosen by the collaborating partner company as representative of the variation used in the footwear market and of the materials that could be used in the heeled style of footwear being investigated.

All shoes were based on the same shoe design and from the same lasts, adjusted for heel height and the heel seat angle (which is coupled to changes in heel height). The midsoles were a wedge design made from cork with a rubber outer sole. Due to the varied heel heights, and as is the case for all heeled shoes, the heel-toe length of the outer sole was shorter for the higher heels which subsequently reduced the total contact area between the shoe and ground.

The wedges had a slight negative medio-laterial flare on both medial and lateral sides, thus the shoe sole was narrower at its base than at the footbed. This flare was consistent in gradient across all shoes and as a result the contact area between the shoe and ground was least in the shoes with the greatest heel heights.

To attempt to keep the toe spring angles similar whilst heel height was increased, material was added below the forefoot thus increasing the thickness of the sole. This did not affect heel height because the *effective heel height* is concerned with the position of the heel and forefoot relative to each other, not the heel and the ground. However, it does increase the distance the participant is from the ground, however this was maintained across all shoe conditions by using the thickness required for the highest heel for all shoes. Thus all the tests were conducted on raised heel shoes with a forefoot wedge.

There were 5 effective heel heights investigated: 35, 45, 55, 65, 75 mm. All shoes had the same last contact point, and the same amount of wedging under the forefoot. There were 15 shoes tested in total (three upper stiffness and 5 heel height for each stiffness) (table12).

Table 10: Variables of the test shoes

Material	Effective heel Height (mm)
Bovine leather	35
Bovine leather	45
Bovine leather	55
Bovine leather	65
Bovine leather	75
Bovine suede	*35*
Bovine suede	*45*
Bovine suede	*55*
Bovine suede	*65*
Bovine suede	*75*
Goat suede	35
Goat suede	45
Goat suede	55
Goat suede	65
Goat suede	75

These shoes were chosen to ensure that the effects on pressure and comfort due to high heels could be seen over a wide range, whilst also, attempting to keep the total number of shoes to a practical limit to avoid fatiguing participants.

The heel heights were set at clear intervals over the range, so that trends could be observed. There were more heel heights than upper materials as the primary goal was to establish the trend associated to heel height and also heel height was felt to vary across a wider range than upper stiffness.

Figure 43: Examples of the shoes used.

4.2.4. Setting

All testing was carried out at the University of Salford in the Brian Blatchford Gait Lab, on a hard laminate floor. The lab is secluded and without windows, thus there is very little that can distract the participant or inhibit them whilst they walk.

4.2.5. Testing Procedure

On arrival the participant was welcomed and an explanation of what would happen during testing given, along with a written copy of the procedure. The participant was reminded that they do not have to take part and they were free to stop participation whenever they choose. When the participant was happy they were asked to sign consent.

Participants were asked to remove their shoes and socks and given a pair of nylon socks to wear. Following this initial process the participants were given the first test shoe and asked to fit the shoe comfortably and tie their own laces. The shoe tightness measurements were taken using a Vernier calliper, as previously described. Participants were given a period of time to acclimatise to the shoes and the required walking speed. This consisted of walking the test area practicing the correct walking speed. The total time the participant wore the shoes prior to collecting data exceeded 5 minutes for the first set of shoes, which enabled familiarisation to the study. For the remainder of the shoes in excess of 166 steps were taken in all cases, as recommended in the previous study (Chapter 3).

The order in which shoes were worn was randomised except for one shoe (bovine suede with a 55 mm effective heel height) which was designated as a “control shoe”. This was tested first, seventh, and thirteenth (i.e. last). The purpose of repeating measurements with this shoe was, to evaluate if participants were consistent in their scoring of the VAS scale throughout the testing process. Use of the control shoe as the seventh shoe was deemed appropriate because past research had shown that participants show good reliability at scoring footwear comfort after 6 conditions [233]. This shoe was also chosen as the control because it represented the middle range of both upper stiffness and heel height.

To comply with the recommendations for a minimum of 30 steps (from chapter 3) for each shoe condition, multiple walks in the test area were required. As a result the participant had to walk numerous lengths of the test area, until sufficient steps had been collected.

The measurements of the foot were taken prior to wearing shoe 13, which is the third time that the control shoe was worn. Socks were removed and the participant was asked to place their foot in the foot scanner. Measurements were taken whilst the foot was flat on the scanner surface. Following this the measurement of the navicular and big toe was taken by hand, and then the third control shoe trial was then completed. It was decided that the foot measurements would be taken before the third control shoe trial in order to break up the testing procedure for the participant. Due to the very repetitive nature of the study there was a concern that the participant would become fatigued (or even frustrated) and this would affect either their scoring of the VAS or their ability to maintain consistent gait whilst walking.

4.3. Data processing

4.3.1. Plantar pressure data:

As discussed in the previous chapter 'masks' identifying anatomical regions of interest are often used when investigating plantar pressure distribution. In the previous chapter the development of a mask suitable for this thesis was also discussed and the data for this study was processed using the same masks. Plantar pressure data was therefore derived for the following regions: 1st metatarsophalangeal joint (MTP1), 2nd–4th metatarsophalangeal joints (MT24), the hallux, 5th metatarsophalangeal (MT5), the heel, and the midfoot.

The data steps from the acceleration, deceleration and pausing phase executed at each end of the walking area, were clearly visible because the participant was asked to stop before they turned at each end of the lab. A MATLAB code was written that removed the steps before and after the participant stopped, leaving only the steps taken whilst walking in a straight line at the speed measured by the timing gates. This is consistent with past studies (e.g. Arts and Bus [26]). At least 30 acceptable left foot steps were collected and the pressure values from each individual sensor were averaged to produce an average step for each participant in each shoe condition, which is consistent with the recommendations of chapter 3.

4.3.2. Foot Measurement

A 3D scan of both the foot and shoe last was required to characterise the difference between these two shapes, and investigate whether this difference related to the effects of heel height and upper stiffness on pressure and comfort. Whilst the scanner provides the surface geometries, a method was required to parameterise the differences in foot and last shapes. An investigation was carried out to establish which method would provide the necessary geometric data

Identifying an approach to compare foot and last shape

In order to provide measurements of the foot that can be used in the development of lasts, the measurements of the foot must be easy to compare to similar measurements of the lasts. Since there is variability between participants' feet for the location at which measurements are taken (i.e. the percentage of foot length at which the widest part of the foot occurs) but not the last, a method of measuring the feet that enables comparison with the last is required. A small investigation was carried out to identify a repeatable way of quantifying the differences between the foot and last shape, to enable comparison across a range of heel heights. The system chosen is that which produces the least variable measurements of the foot and enables ease of comparison between the foot and last.

To draw comparison between a range of measurement techniques a set of 3D foot and last scans were required. To acquire these scans 15 participants were recruited. The participants were required to fulfil the same inclusion criteria as the main study in this chapter. All participants had their foot shape scanned, in a flat position with the foot resting on the glass of the scanner and in two raised heel positions using a peace of EVA wedging under the foot (72mm and 36mm). The scans produced a point cloud which was made into a mesh of the foot, which was then measured using the three following approaches:

1) Anatomical measurements from landmarks of the foot (as visible on screen),

2) INESCOP measures taken with the INFOHORMA software

3) foot girth at 73% of foot length adopted by (from Wunderlich and Cavanagh 2001) [32].

- The anatomical measurements consisted of the foot length which is the distance between the most extreme distal (TF) and proximal (HF) points as shown in Figure 44, the waist girth at the ball (ball girth), the inclination angle which is the angle between the vertical and the plane which the ball girth is completely contained within (girth plane), the torsion or ball angle which is the angle between the ball plane and a plane perpendicular to the foot axis (line from HF to tip of second toe).
- For the INFOHORMA measurements these were the same as the anatomical measurements except the girth measurement which was taken at 65% of foot length.
- For the Wunderlich system the girth was measured at 73% of foot length and it does not have an inclination angle, the ball girth is instead measured in the plane perpendicular to the foot axis.

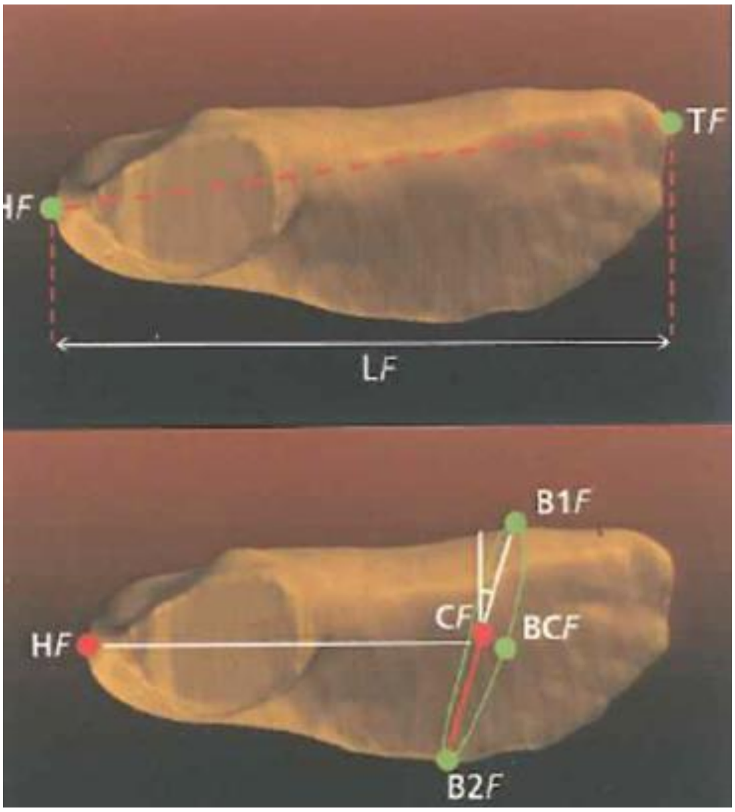

Figure 44: The foot length.
Diagrams taken from the INESCOP scanner users' manual (top), The torsion angle, diagram taken from the INESCOP scanner users' manual. Where HF is the back most point of the foot, TF is the front most point of the foot, B1F is the medial metatarsal head point, B2F is the lateral metatarsal point, and CF is the middle metatarsal point (the midpoint between B1F and B2F)

A total of 15 participants completed this investigation (age: 27.4 ± 6.3 years, weight 57.6 ± 6.3 kg, height 163.2 ± 5.5 cm).

When processing the foot scans it was found that the wedging technique used to elevate the heel was unsuccessful. The wedging material blocked the scanner from measuring the plantar surface of the foot. Initially it was believed that this wouldn't pose a problem because the wedging material ended just before the forefoot, the primary region of interest. However, having an alien object in the scan volume distorted the mesh algorithms thus rendering the scans unusable. It was assumed that using the filtering techniques similar to that used to remove error generated by ambient light would overcome this problem. However, this was unsuccessful as it left large holes in the surface point clouds and these also distorted the final mesh, making any subsequent measurement invalid.

All three foot measurement approaches provided a measure of foot girth at a specific percentage of foot length. Using a percentage ensures the results were naturally normalised against foot/shoe size. To get repeatable measurements of the foot an anatomical measurement was thought to be best to ensure consistency of measurement because it uses the foot's anatomical landmarks. However, using the foot's landmarks introduces the natural variability between participants, making it difficult to compare the measurements of the foot to similar measurements on the last. For example whilst you may choose to measure the width of the foot at the metatarsal heads, where this measurement is taken relative to foot length would change from person to person but the widest part of the last would remain the same. Thus, it is not clear what location on the lasts corresponds to the metatarsal heads on the foot for any given person. A further limitation to using foot landmarks was the type of scanner used. With this scanner it is not possible to locate landmarks accurately, and instead estimations of anatomical locations are taken from the scan. For example, it is not possible to locate the metatarsal heads, instead the widest part of the forefoot is used and the investigator edits this to where they think the metatarsal heads are on screen. This process could therefore introduce error due to the investigator making estimations. The anatomical measurement technique had by far the largest variability with a standard deviation of 22.5 for measurements of the girth, compared to 11.6 and 9.8 for the Wunderlich and INESCOP systems respectively.

The reduction in variability was not the only added benefit to the INESCOP system. Further variations exist between individuals including the ball and inclination angles, which are used when a last maker is designing a last. In order to avoid discrepancy in measurements it is logical to consider the ball an inclination angle when measuring the foot. Despite this fact, these measurements are not considered in the Wunderlich system. Furthermore, from the anatomical measurements taken when the systems were compared, it was found that the widest part of the foot was on average 62.8% (SD =8.4) of foot length. This is slightly less than that recommended by INESCOP, however, it is almost 10% less than that recommended by the Wunderlich system [32]. Thus to conclude the system developed by INESCOP provides the least variability of the systems considered shown by its low standard deviation value, provided the best comparison to the last because it consisted of measurements similar to those taken by the last maker and at similar locations. Due to these factors the INESCOP system produced the most useful information for last makers and thus will be used for the measurements in the main study.

In the final investigations the following method of measuring the foot were conducted: To run Pearson's comparisons between the change in comfort rating and the difference in volume the standard ball length was set at 65% of last length, the ball angle was 12° and the inclination angle of the ball was set at 21.4° for both the last and foot measurements. The difference between the last and foot girths could then be found (foot values subtracted from last values, thus a negative value shows that the foot is larger than the last).

4.3.3. Discomfort questionnaire:

Data from the VAS was measured and the results averaged across the participants, so that there was a score that represented all the participants for each question whilst wearing each shoe.

4.4. Statistical Analysis

The statistical analysis for this study was completed using SPSS statistics software package (version 22). The analysis was as follows:

- A within-within (two way) ANOVA design, with repeated measures was used to establish the effects of heel height (research aim 1A) and material stiffness (research aim 2A) on plantar pressure. A separate ANOVA test was conducted for each of the separate anatomical regions defined in the mask.
- A within-within (two way) ANOVA design, with repeated measures was used to establish the effects of heel height (research aim 1B) and material stiffness (research aim 2B) on comfort. Pearson's correlations were also tested on all of the questions asked in the questionnaire for each heel height and material stiffness.
- ANOVA tests were used to test for an interaction between the heel height and material stiffness on plantar pressure (research aim 3A) and comfort (research aim 3B).
- An ANOVA with repeat measures was used to establish if there was significant difference between the three repeated trials of the control shoe. This was conducted on data for all of the pressure region and comfort questions.

To establish if the tightness of lacing (research aim 4) or forefoot fit (research aim 5) can affect the results of research aims 1-3, the Pearson's correlation was used. The four relationships investigated were:

- fit vs pressure,
- fit vs comfort (for each comfort question asked),
- lacing vs pressure,
- lacing vs comfort (for each comfort question asked)

Correlation was deemed significant at the 0.05 level (2-tailed) and an adjustment using Bonferroni correction was used for multiple comparisons. These tests were also carried out for each of the upper material and heel height subgroups in order to reduce the effect of multiple variables. Due to the large number of tests, regression graphs were produced in excel for those that were significant in order to aid the discussion of results.

A further comparison was carried out to establish if there was a correlation between pressure and comfort, using the regression (R^2 value) produced in excel.

4.5. Results

4.5.1. Effects on plantar pressure

4.5.1.1 Overall effect of increased material stiffness and heel height:

The main effect of increased upper material stiffness was to move pressure from under MT24 to below MTP1. With an increase in material stiffness from the softest (goat suede) to the medium (bovine suede) plantar pressure under MTP1 increased by 5% and pressure under MT24 decreased of 8%. Between the softest and the stiffest upper (bovine leather) only the pressure under MTP1 significantly increased by 8%. The ANOVA revealed that there was a significant effect due to material stiffness on the hallux however this was not observed in the pairwise comparisons.

With increased heel height there was an increase in pressure under the MTP1 (41% increase from 35mm to 75mm heel) and MT24 (33% increase from 35mm to 75mm heel), and a reduction in pressure under the heel (22% reduction from 35mm to 75mm heel) and hallux (21% reduction from the 35mm to the 75mm heel). These results show that increasing heel height by an increment of 10 or 20mm is sufficient to significantly increase the pressure under the MTP1.

The only region that had a significant difference in pressure for the repeat trials was the MT24. This region showed trial one to be significantly different from trial two (p=0.029) and trial three (p=0.020).

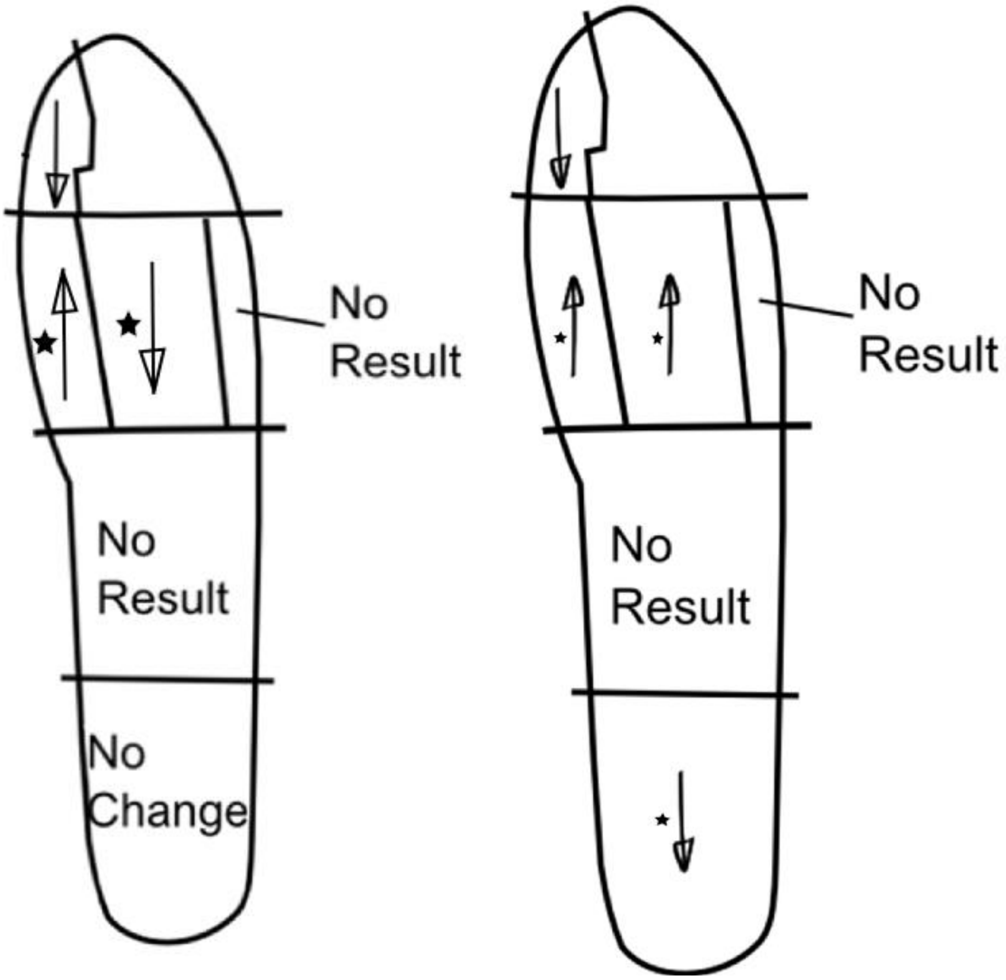

Figure 45: The effects on pressure due to increases in upper material stiffness (left) and increases in heel height (right).
'no result' shows that pressure values found were lower the reliable range of the sensors, 'no change' shows that there was no significant change, a down arrow shows an increase in material stiffness reduced pressure, an up arrow shows an increase in material stiffness increased pressure, and a star shows that there was significance for both ANOVA and a pairwise comparison t test. The same effect was seen as a significant difference in the pairwise comparison

4.5.1.2. Region specific affects due to heel height and material stiffness on plantar pressure and comfort.

MTP1

An increase of both heel height and material stiffness produced a significant increase in the pressure recorded beneath the MTP1. From a 35mm heel to a 75mm heel there is an increase in pressure of approximately 46%. The results show that a 20mm increase in heel height (i.e. 35mm to 55mm, or 45mm to 65mm) is required to produce a significant 19%

increase in plantar pressure. Between 55 and 65mm the 10mm increase was sufficient to produce statistically significant change in peak pressure.

Mauchly's test showed that the data was spherical only for material stiffness ($X^2(2)=0.568$). From the ANOVA results it is clear that there was a significant main effect due to the material stiffness ($F(2,28)=4.948$ $p=0.014$) which shows that an increase in material stiffness produces an increase in plantar pressure at the MTP1. A pressure change between each of the three materials was circa 10%. Bonferroni pairwise comparisons show that there was a significant difference between the softest and both the medium ($p=0.037$) and the stiffest materials ($p=0.04$) however there were no other significant differences in material stiffness.

The ANOVA also showed that there was a significant main effect on plantar pressure due to heel height ($F(1.757,24.603)=25.781$ $p=0.000$), which shows that an increase in heel height produces an increase in plantar pressure under MTP1. The Bonferroni pairwise comparisons of heel height show that there was a significant difference between 35mm and 55mm ($p=0.005$), 65mm ($p=0.000$), and 75mm ($p=0.001$). There was a significant difference between 45mm and 65mm ($p=0.000$), and 75mm ($p=0.002$). Finally, there was a significant difference between 55mm and 65mm ($p=0.000$), and 75mm ($p=0.012$).

The interaction between material stiffness and heel height was not significant.

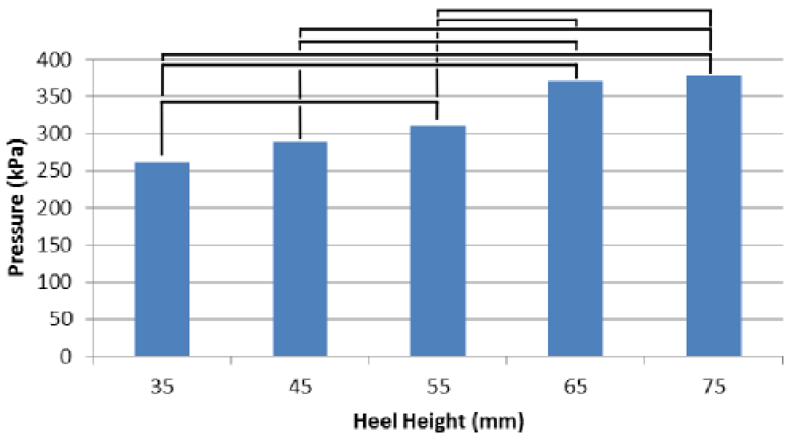

Figure 46: The effect of heel height on plantar pressure in the MTP1 region. Bars denote statistically significant differences (p<0.05).

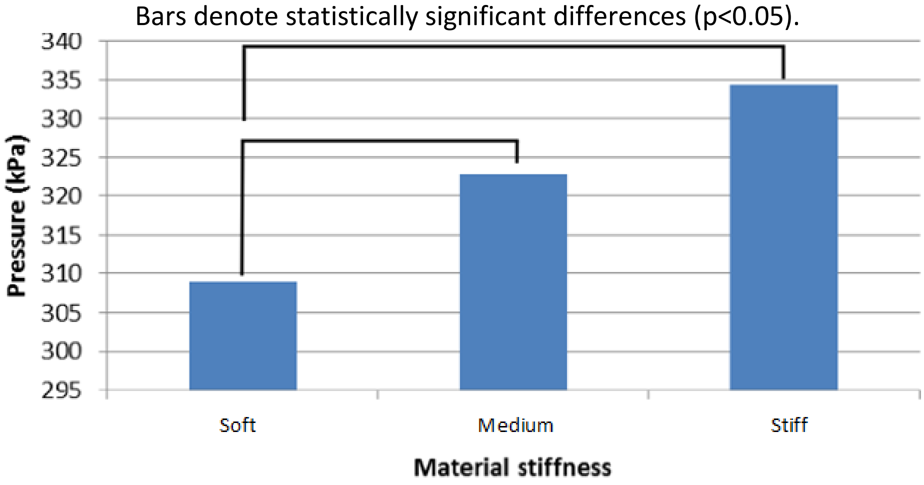

Figure 47: The effect of material stiffness on plantar pressure in the MTP1 region. Bars denote statistically significant differences (p<0.05).

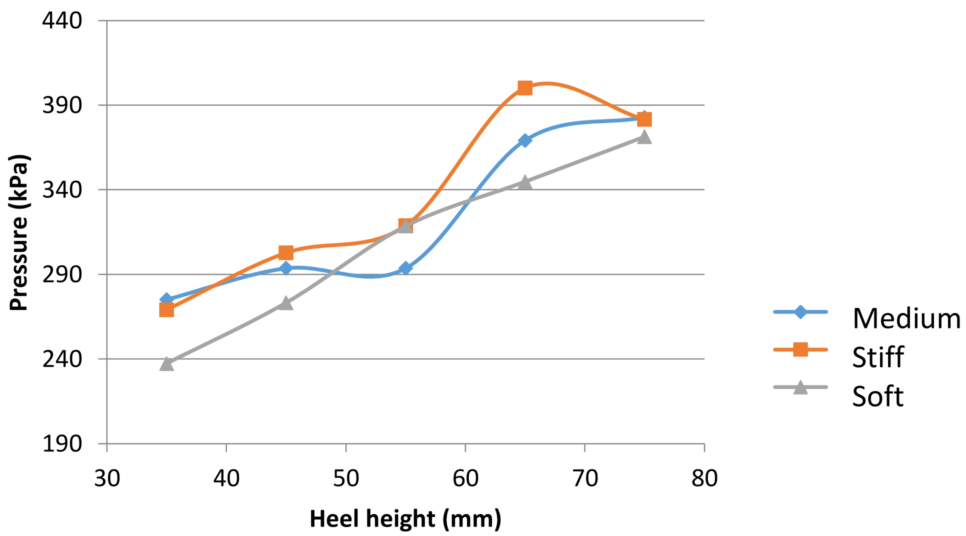

Figure 48: The interaction between heel height and material stiffness on plantar pressure in the MTP1 region

MT24

There was less effect due to heel height at the MT24 compared to MTP1 (33% and 46% change respectively) with very little change across most of the conditions, and the only statistically significant difference being the 75mm shoe compared to all other heel heights ($p<0.05$). The only statistical significant difference for material stiffness below the MT24 was a 7% decrease in pressure between the soft and medium upper shoe conditions, which is opposite of the change under MTP1. The stiff upper produced higher pressures than the medium upper but this was not statistically significant.

The Mauchly's tests showed that the data was not spherical for material stiffness, heel height, or the interaction of heel height and stiffness. The ANOVA tests show that there was a significant main effect due to material stiffness ($F(1.348,18.873)=4.427$, $p=0.039$). The Bonferroni pairwise comparisons shows that there was only one significant difference for the material stiffness and that was between the soft and medium materials ($p=0.007$).

The ANOVA tests show that there was a significant main effect due to heel height ($F(1.495,20.925)=21.371$, $p=0.000$). Whilst the Bonferroni pairwise comparison show that there was a significant difference between the 75mm heel and all other heel heights (35mm $p=0.002$, 45mm $p=0.001$, 55mm $p=0.001$, 65mm $p=0.000$) but there was no significant difference between any other conditions. There was not a significant main effect due to the interaction between material stiffness and heel height.

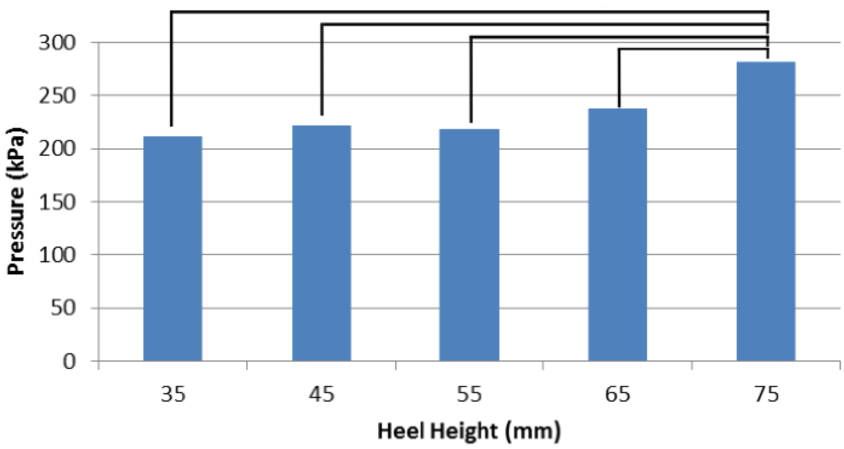

Figure 49: The effects of heel height on plantar pressure in the MT24 region. Bars denote statistically significant differences (p<0.05).

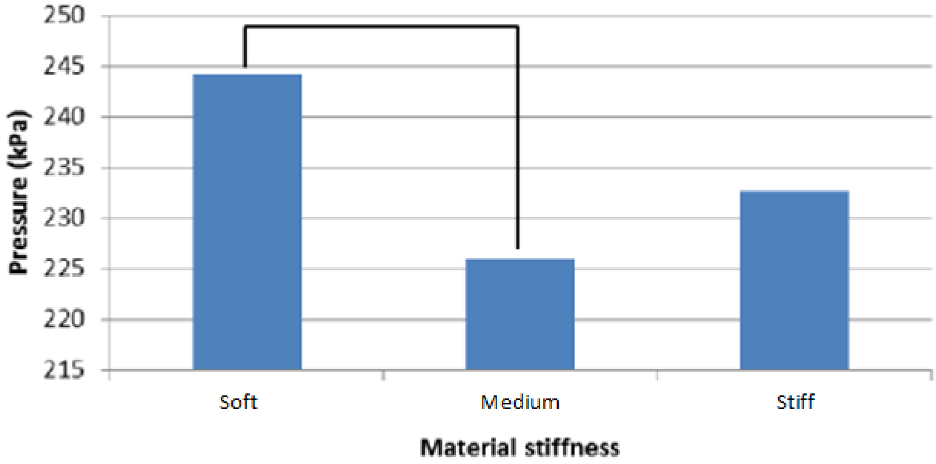

Figure 50: The effects of material stiffness on plantar pressure in the MT24 region. Bars denote statistically significant differences (p<0.05).

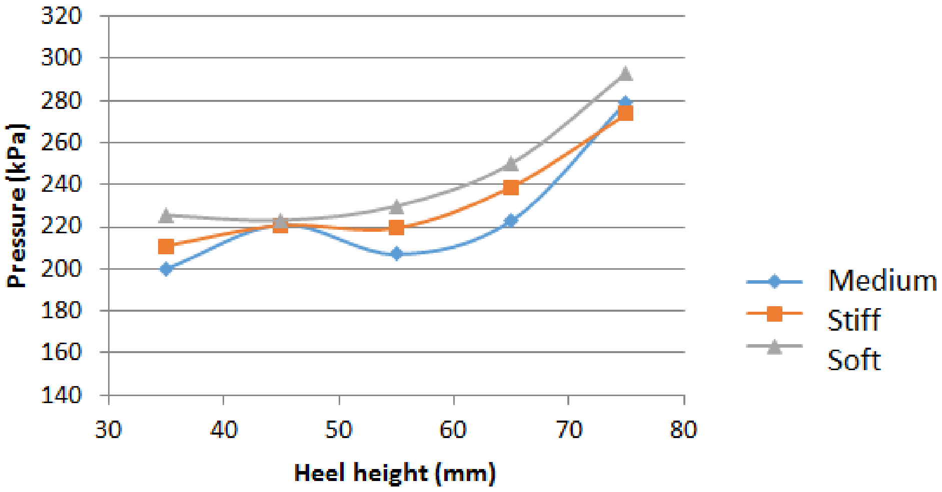

Figure 51: The interaction between heel height and material stiffness on the plantar pressure in the MT24 region

Hallux

Mauchly's test shows that the data was spherical for material stiffness ($X^2(2)=0.119$) only. The ANOVA results show that there was only a significant main effect due to heel height ($F(1.966,27.530)=4.088$, $p=0.028$) on plantar pressure. For the hallux there was a 21% change in plantar pressure with the 75mm heel producing the lowest plantar pressure and the 35mm heel the highest plantar pressure. The effect due to material stiffness was close to significance but ultimately was not ($F(2,28)=3.152$ $p=0.058$). The Bonferroni comparisons showed that there was no significant difference between any two conditions.

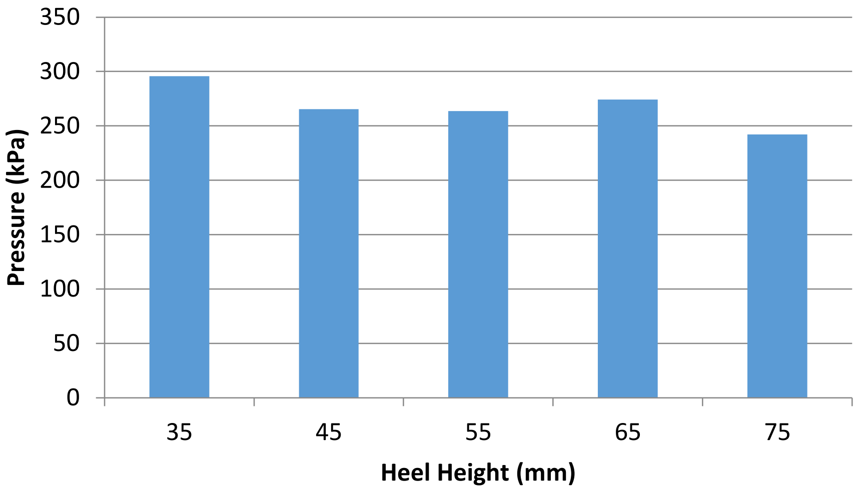

Figure 52: The effect of heel height on plantar pressure in the hallux region

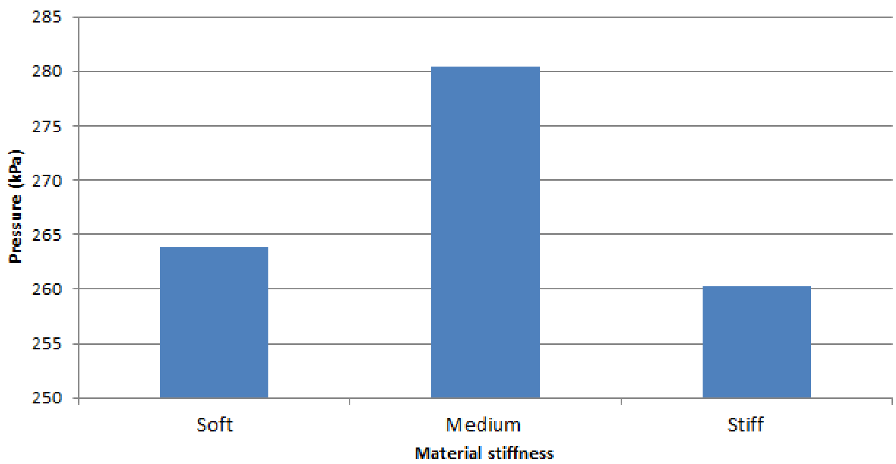

Figure 53: The effect of material stiffness on plantar pressure in the hallux region

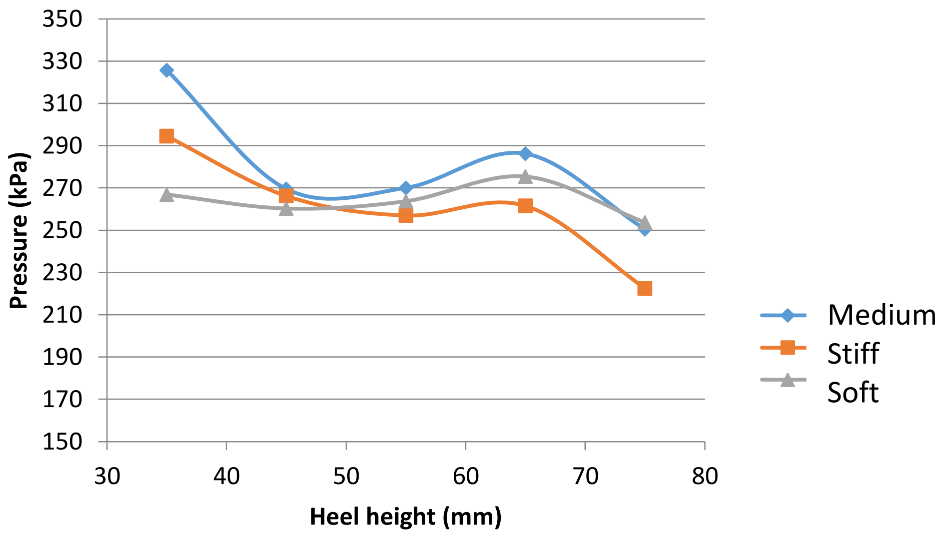

Figure 54: The interaction between heel height and material stiffness on plantar pressure in the hallux region

Heel

The Mauchly's test revealed that only the material stiffness was spherical ($X^2(2)=0.365$). The ANOVA results show that there was only a significant main effect due to heel height ($F(1.964,27.501)=5.655$ $p=0.009$). The Bonferroni pairwise comparisons show that there was no significant difference due to material stiffness but there was due to heel height. The lowest (35mm) and highest (75mm) shoes were significantly different ($p=0.007$) with an 18% reduction in pressure when the heel was raised. The 45mm shoe and the 75mm shoe see a similar size significant reduction when heel was raised ($p=0.039$).

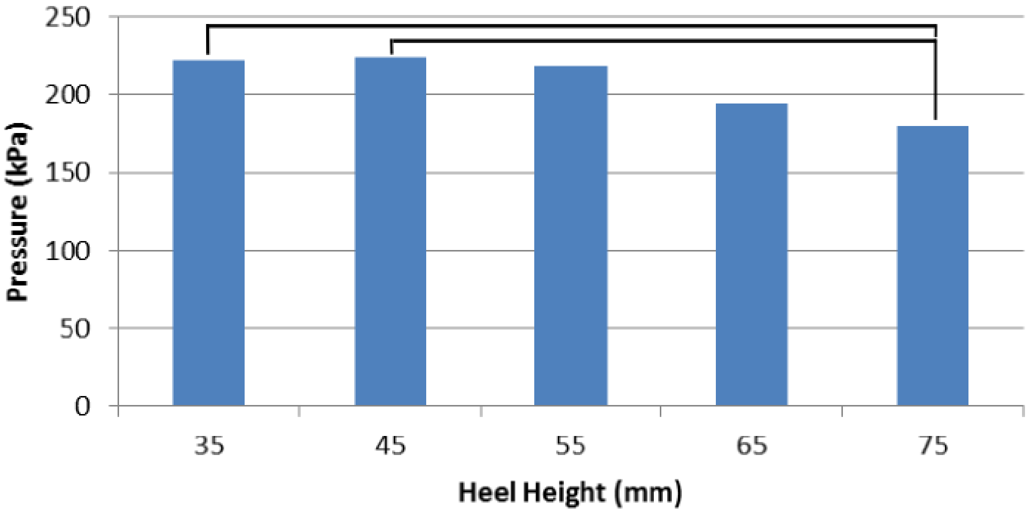

Figure 55: The effects of heel height on plantar pressure in the heel region. Bars denote statistically significant differences ($p<0.05$)

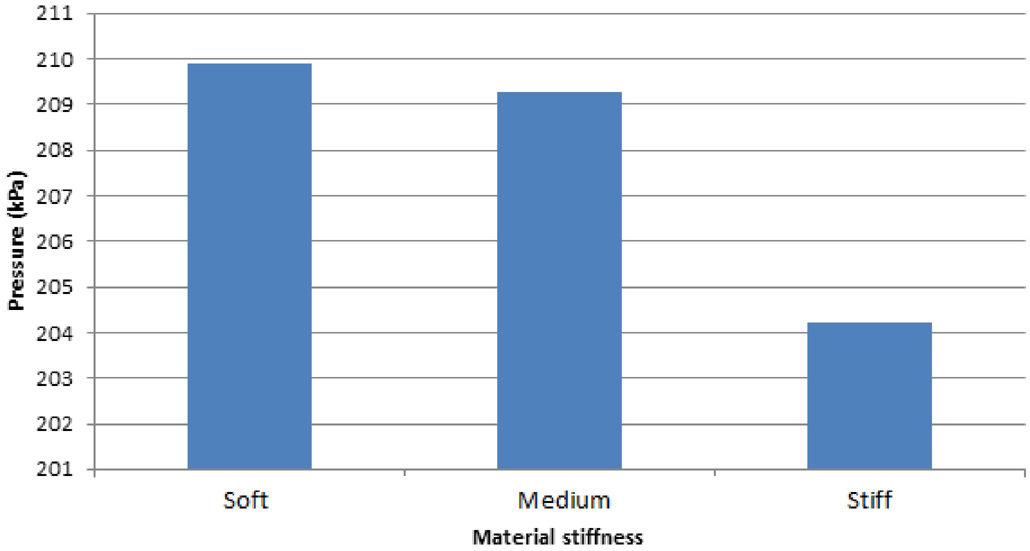

Figure 56: The effects of material stiffness on plantar pressure in the heel region

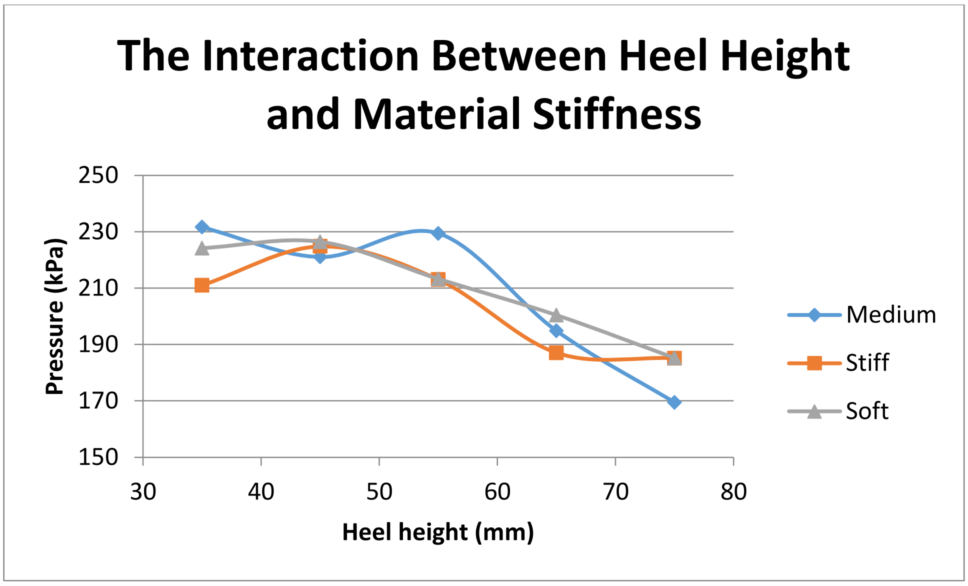

Figure 57: The interaction between heel height and material stiffness on plantar pressure in the heel region

4.5.2. Effects of discomfort

An overview of the effects on discomfort

A brief overview of the comfort data is provided here as a precursor to a more detailed presentation of results and statistical outcomes.

The data indicates that there is a clear significant effect of both material stiffness and heel height on the comfort of a shoe. An increase in heel height from 55 to 75mm resulted in a significant increase in discomfort ($P<0.05$) at all foot locations, except on the dorsal surface of the foot and the sides of the metatarsal heads. The participants reported that they experienced had significantly increased discomfort at the dorsal surface between the 35mm and 75 mm heel heights ($p<0.05$). The areas that were most susceptible to change in comfort due to changes in heel height were the overall length, medial arch, and the toes. The comfort related to the sides of the metatarsal heads showed no significant changes in comfort due to changes in heel height.

Medial arch comfort was the only area to not report statistically significant change in comfort due to changes in material stiffness. The overall length did show a significant effect but it was not evident from the pairwise comparisons between which materials this effect occurred. In all other regions there was a significant difference between the medium and stiffest material and between the softest and stiffest material. There was a significant difference between the soft and medium upper only for the dorsal surface.

The repeated measurements taken whist the control shoe was worn were compared. For these repeat measurements three questions showed a statistically significant result between trials; comfort on top of the foot between repeated trials one and two (p=0.047), the side of the balls of the feet between repeated trials one and three (p=0.031) and the sole of the balls of the feet between repeated trials one and three (p=0.031), in all cases the difference occurred between the first repeated trial and one other.

Overall discomfort

Mauchly's test showed that only the heel height data was spherical ($X^2(9) = 23.655$). Heel height had a main effect on overall discomfort ($F(4,56)=7.656$, $p=0.000$). The Bonferroni pairwise comparisons of heel height showed that only two conditions were significantly different, the 35mm heel compared to the 75mm heel (p=0.021, 74% increase) and the 55mm heel compared with the 75mm (p=0.000, 64% increase).

From the ANOVA results it was apparent that there was a significant main effect due to material stiffness ($F(1.960,27.438)=13.365$,$p=0.00$). Bonferroni pairwise comparisons show that there is a significant difference between the softest and stiffest material (p=0.004, 48% increase) as well as the medium and stiff material (p=0.001, 58% increase) but there was not a difference between the soft and medium material.

Both material stiffness and heel height show a general trend whereby increasing them increased discomfort. From the interactions plot (Figure 60) it is apparent that there is some difference in the response to heel height when wearing different materials. Specifically the soft material had a more linear response to changes in heel height, and the stiff upper shoe has increased discomfort score for all shoes. Despite this visual observation the interaction between heel height and material stiffness was not statistically significant.

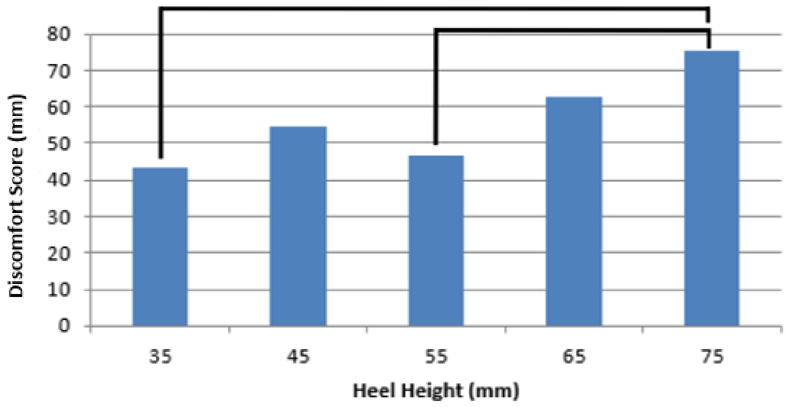

Figure 58: The effects of heel height on overall shoe discomfort.
Bars denote statistically significant differences ($p<0.05$)

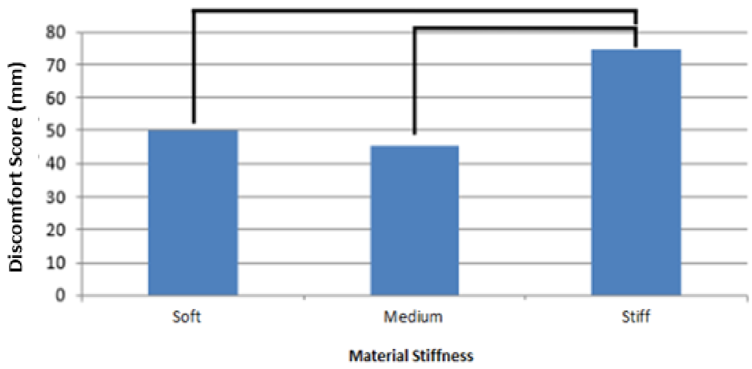

Figure 59: The effect of material stiffness on overall shoe discomfort.
Bars denote statistically significant differences ($p<0.05$)

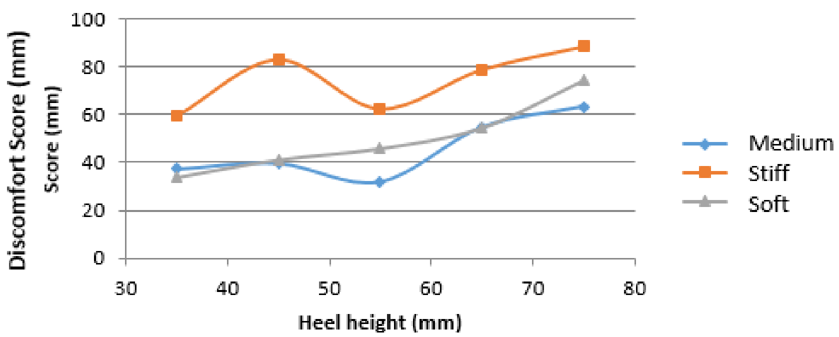

Figure 60: The interaction between heel height and material stiffness on plantar pressure on the overall shoe discomfort.

Overall width related discomfort

Mauchly's test showed that the data was spherical for heel height ($X^2(9)=19.376$) only. The ANOVA tests reveal that there is a significant main effect for material stiffness ($F(1.696, 23.744)=8.908$, $p=0.002$) and heel height ($F(4,56)=5.090$, $p=0.001$). The Bonferroni pairwise comparisons revealed that there was There was also a significant difference for heel height where the highest 75mm shoe was different to the lowest 35mm heel ($p=0.030$, 44% change) and the 55mm heel ($p=0.047$, 38% change). There was also, a significant difference between the stiffest and both the softest ($p=0.006$, 38% reduction from stiff to soft) and the medium material ($p=0.011$, 57% reduction from stiff to soft).

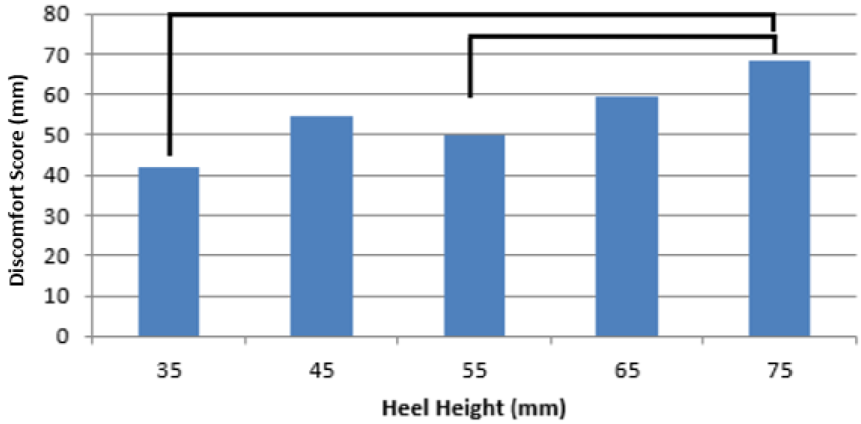

Figure 61: The effect of heel height on the overall width discomfort. Bars denote statistically significant differences ($p<0.05$)

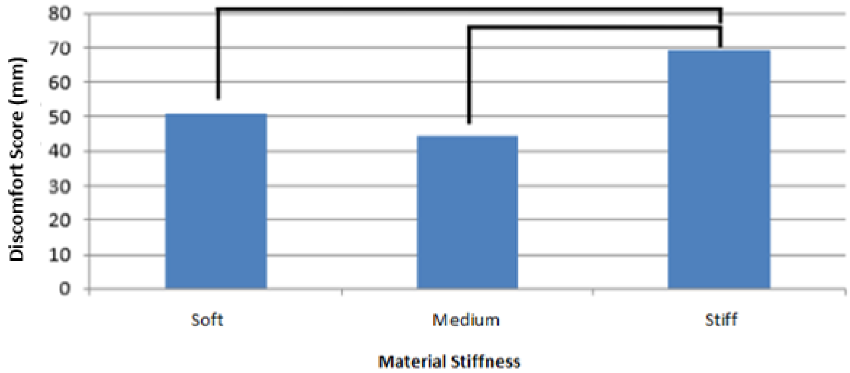

Figure 62: The effect of material stiffness on the overall width discomfort. Bars denote statistically significant differences ($p<0.05$)

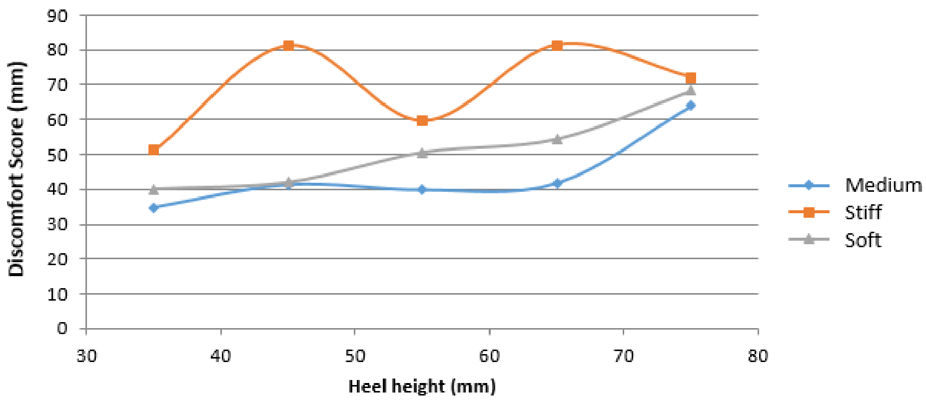

Figure 63: The interaction of material stiffness and heel height on overall width discomfort.

Overall length related discomfort

Mauchly's test revealed that the data was not spherical for any of the three tests (material stiffness, heel height, or the comparison of heel height to material stiffness). The ANOVA test showed that there was a significant main effect due to material stiffness ($F(1.572,22.008)=4.022$, $p=0.041$), however the Bonferroni pairwise comparisons show that there was not a significant difference between the materials tested.

The results show that length discomfort (fit due to the heel toe length of the shoe) is increased as heel height is increased ($F(2.376,33.258)=7.684$, $p=0.001$), with a clear difference between shoes that have <65mm compared to those >65mm. Bonferroni pairwise comparisons showed there was a significant difference between the highest (75mm) shoe and the lowest (35mm) shoe ($p=0.030$, 86% reduction), 55mm ($p=0.031$, 59% reduction) and 65mm ($p=0.041$, 35% reduction) shoes. There was also a significant difference between the 45mm shoe and the 35mm ($p=0.044$, 40% reduction) shoe.

The ANOVA tests also revealed that there was a significant main effect for the interaction between material stiffness and heel height ($F(5.172,72.414)=3.553$, $p=0.006$)

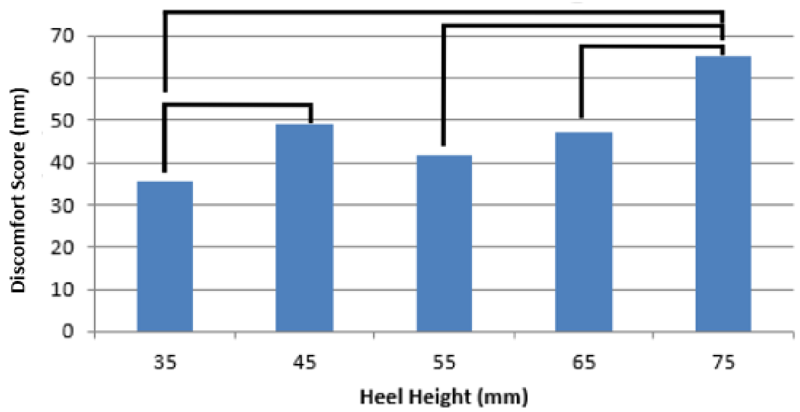

Figure 64: The effect of heel height on overall length discomfort. Bars denote statistically significant differences (p<0.05)

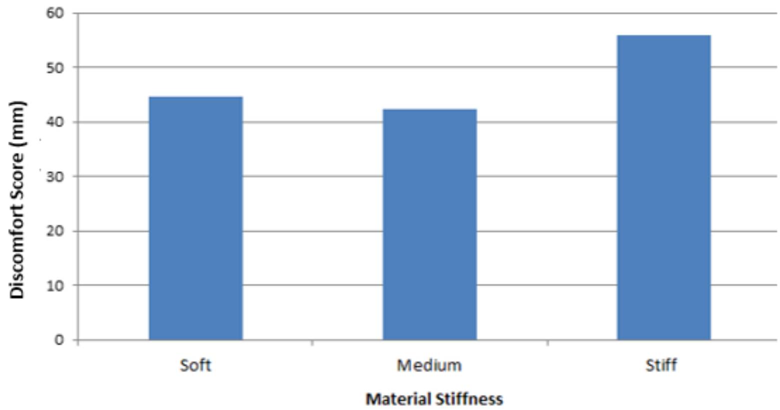

Figure 65: The effect of material stiffness on overall length discomfort.

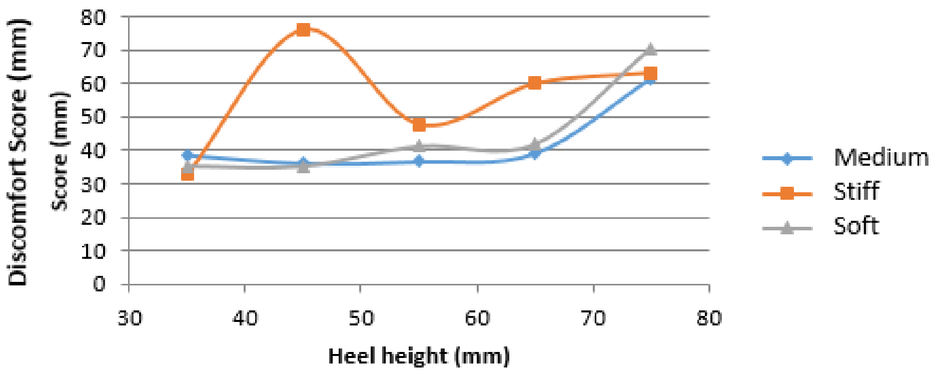

Figure 66: The interaction between heel height and material stiffness on overall length discomfort.

Heel sole related discomfort

Mauchly's test showed that the data was spherical for heel height ($X^2(9)=23.285$) and for the interaction of material stiffness and heel height ($X^2(35)=81.333$). From the ANOVA results it is apparent that there is a significant main effect due to material stiffness ($F(1.873,26.224)=14.806$, $p=0.000$) and heel height ($F(4,56)=4.582$, $p=0.003$). It is therefore apparent that an increase in heel height or material stiffness produces an increase in the discomfort score achieved and therefore a reduction in the comfort. Bonferroni comparisons reveal that there is one comparison for heel height that was significant and that was between the 55m and 75mm heel ($p=0.011$, 35% increase). There is also a significant difference between the stiffest and both the softest ($p=0.002$, 44% reduction) and medium material ($p=0.001$, 44% reduction).

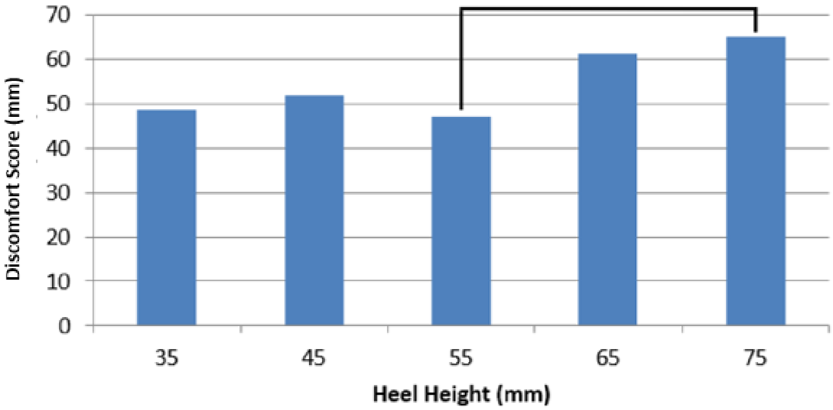

Figure 67: The effect of heel height on the discomfort of the sole in the heel region. Bars denote statistically significant differences ($p<0.05$)

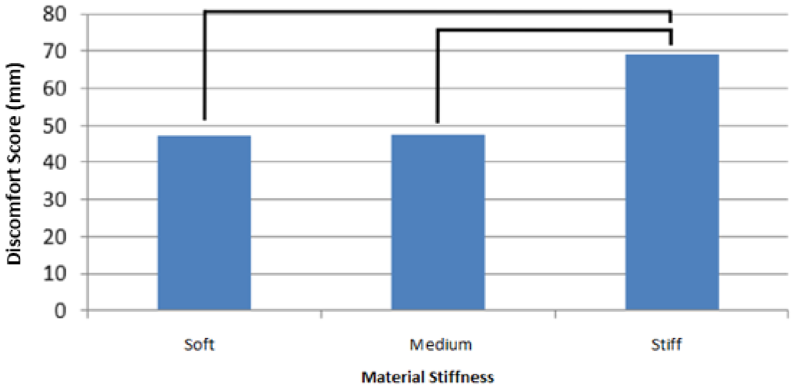

Figure 68: The effect of material stiffness on the discomfort of the sole in the heel region. Bars denote statistically significant differences ($p<0.05$)

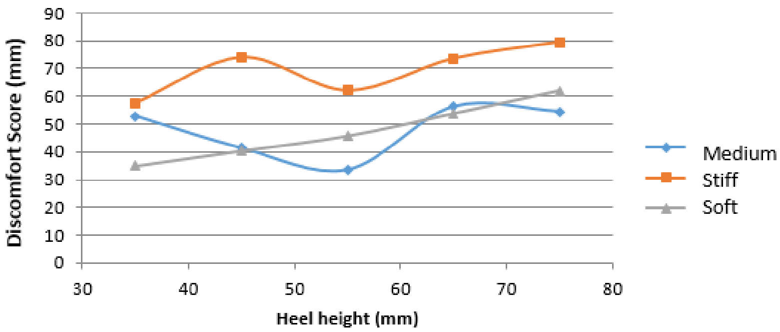

Figure 69: The interaction between heel height and material stiffness on the discomfort of the sole in the heel region.

Heel back related discomfort

Mauchly's test showed that the data was spherical for heel height ($X^2(9)=28.442$) and for the interaction of material stiffness and heel height ($X^2(35)=78.103$). From the ANOVA tests it was apparent that there was a significant main effect on heel back discomfort due to material stiffness ($F(1.977,27.672)=16.055$, $p=0.000$) as well as the interaction of heel height and material stiffness ($F(8,112)=2.193$, $p= 0.033$). An increase in material stiffness and heel height produced an increase in heel back discomfort. Bonferroni pairwise comparisons show that there is a significant difference in discomfort scores between the 55mm and 75mm heel ($p=0.000$, 30% increase). There is also a significant difference between the softest and stiffest materials ($p=0.001$, 44% increase) as well as the medium material and the stiffest material ($p=0.001$, 50% increase).

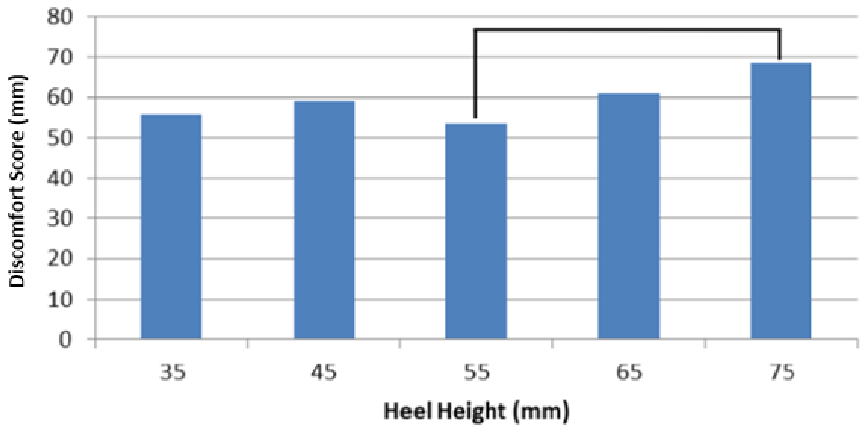

Figure 70: The effect of heel height on discomfort at the back of the heel. Bars denote statistically significant differences ($p<0.05$)

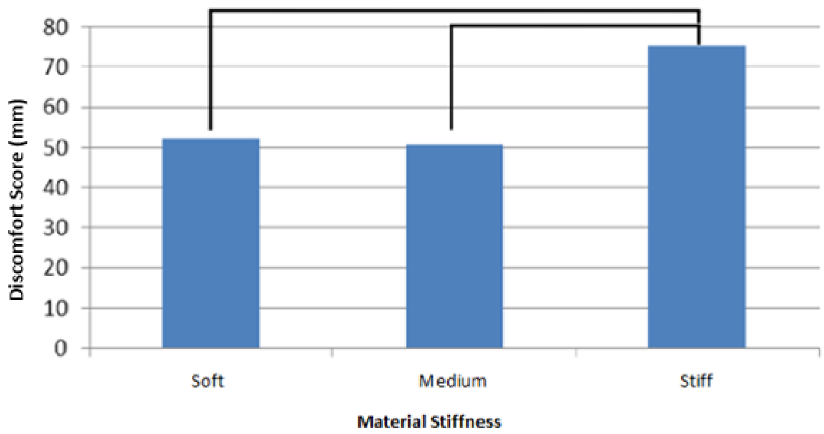

Figure 71: The effect of material stiffness on discomfort at the back of the heel. Bars denote statistically significant differences ($p<0.05$)

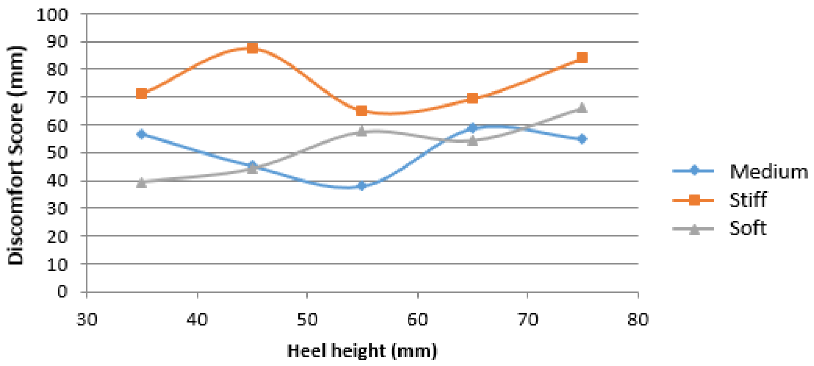

Figure 72: The interaction between heel height and material stiffness on discomfort at the back of the heel

Dorsal surface related discomfort.

Mauchly's test showed that the data was spherical for the interaction of material stiffness and heel height (X^2(35) = 65.667). ANOVA results show that there was a significant main effect on dorsal discomfort due material stiffness ($F(1.870,24.304) = 19.477$, $p = 0.000$) and heel height ($F(3.100,40.304)=4.778$, $p=0.006$). There was a general trend that an increase in heel height was associated with increased dorsal foot surface discomfort, although only the Bonferroni pairwise comparison between the lowest (35mm) heel and the highest (75mm) heel was significant ($p=0.025$) which had a 66% increase. Bonferroni pairwise comparisons show that there is a significant difference between all the materials. A significant differences between the medium material and both the softest ($p=0.44$, 22% increase) and stiffest material ($p=0.000$, 63% increase) indicating that the medium material was the most comfortable. The softest material was the second most comfortable with a significant difference to the stiffest material ($p=0.006$, 33% increase).

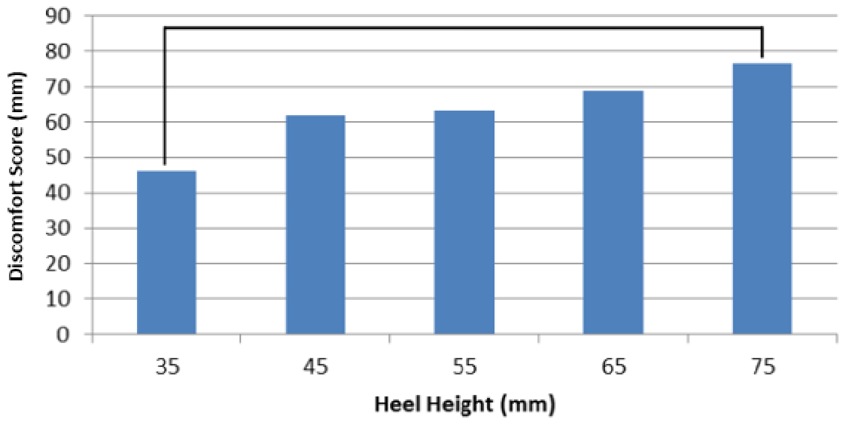

Figure 73: The effect of heel height on discomfort on top of the dorsal surface of the foot. Bars denote statistically significant differences (p<0.05)

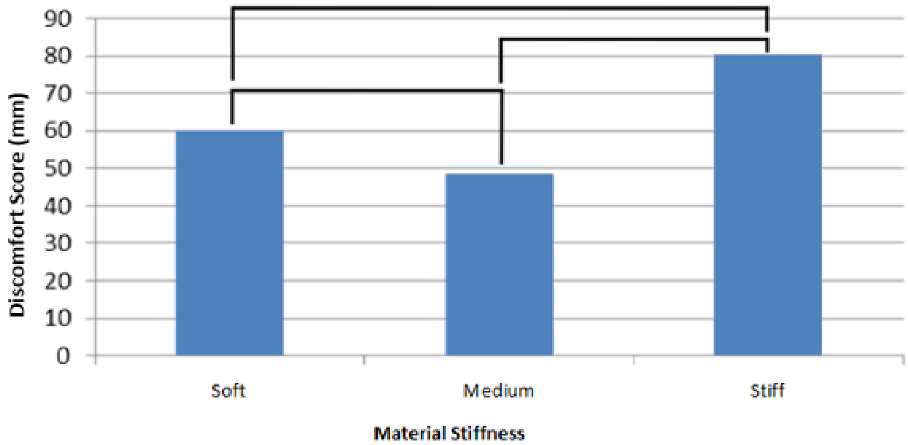

Figure 74: The effect of material stiffness on discomfort on top of the dorsal surface of the foot. Bars denote statistically significant differences (p<0.05)

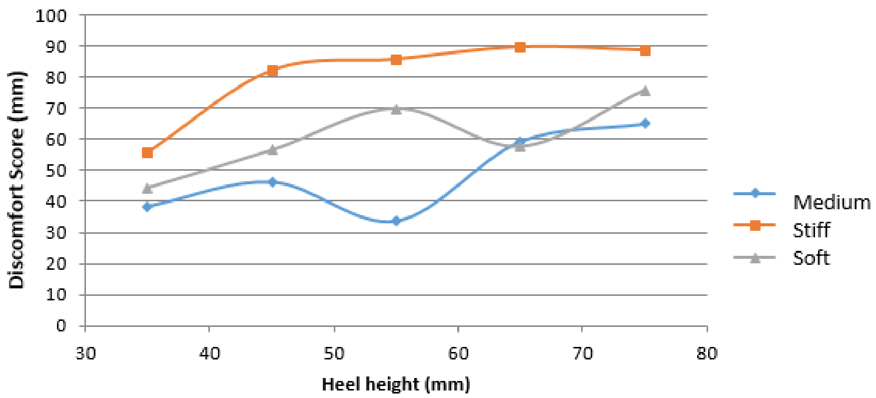

Figure 75: The interaction between heel height and material stiffness on discomfort at the dorsal surface of the foot.

Ball of foot sides discomfort

Mauchly's test showed that the data was not spherical for any of the conditions. From the ANOVA tests it was clear that there was a significant main effect due to material stiffness ($F(1.804,23.446)=6.962$, $p=0.005$), and heel height ($F(2.447,31.816)=5.139$, $p=0.008$), but not the interaction of heel height and material stiffness. The Bonferroni pairwise comparisons show that there was a significant difference between stiffest and both the softest ($p=0.042$, 23% reduction) and the medium material ($p=0.017$, 33% reduction). There were no other significant differences for the effect of heel height on ball of foot side discomfort.

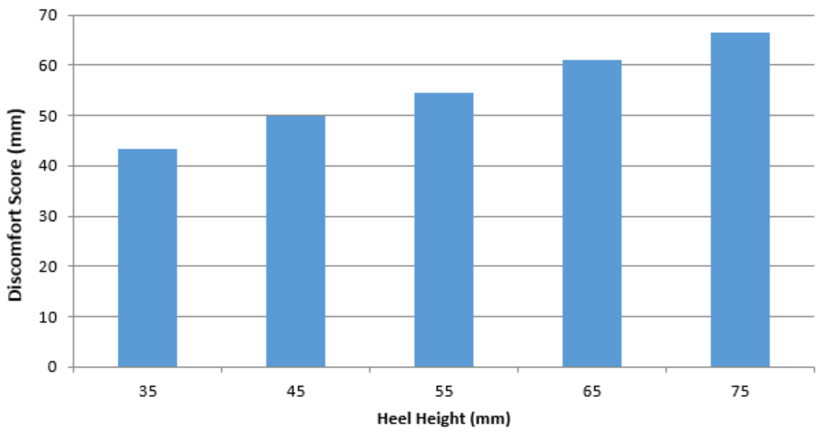

Figure 76: The effects of heel height on discomfort at the sides of the ball of the foot.

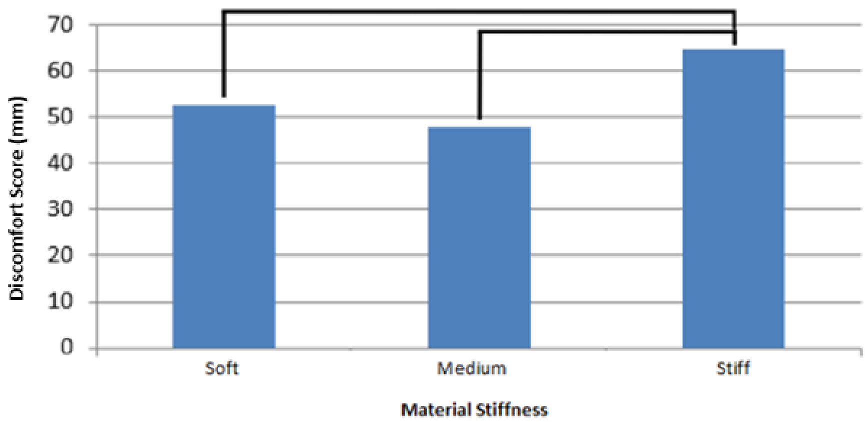

Figure 77: The effect of material stiffness on discomfort at the sides of the ball of the foot. Bars denote statistically significant differences ($p<0.05$).

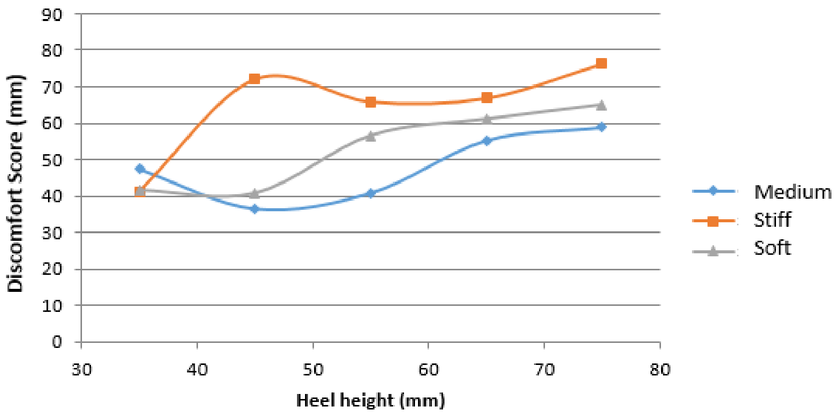

Figure 78: The interaction between heel height and material stiffness on discomfort at the sides of the ball of the foot

Ball of foot sole discomfort

The Mauchly's test showed that the data was spherical for all three tests, material stiffness ($X^2(2)=10.227$), heel height ($X^2(9)=26.205$), and the interaction of material stiffness and heel height ($X^2(35)=75.034$). From the ANOVA test it was revealed that only the interaction between material stiffness and heel height had a significant main effect on ball of foot sole discomfort ($F(4,52)=3.054$, $p=0.004$). The Bonferroni pairwise comparison showed that for heel height there was only a significant difference between the 55mm and 75mm heel ($p=0.005$, 50% increase). There was a significant increase in discomfort between the softest and stiffest material ($p=0.019$, 44% change).

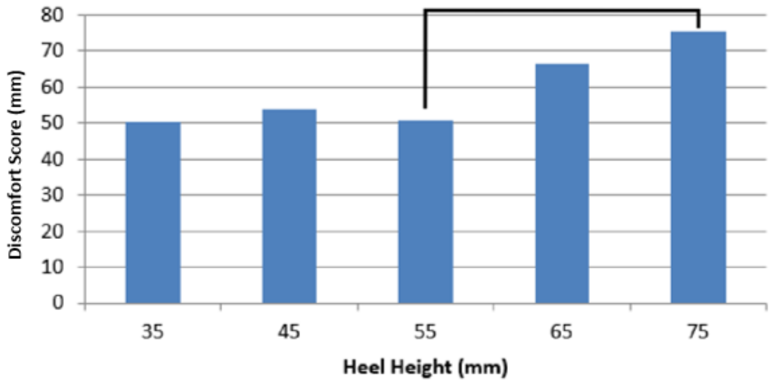

Figure 79: The effect of heel height on discomfort of the sole under the ball of the foot. Bars denote statistically significant differences ($p<0.05$)

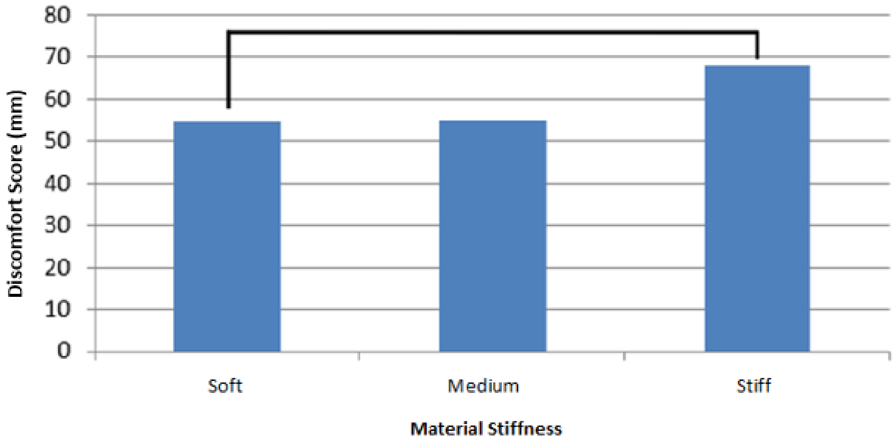

Figure 80: The effect of material stiffness on discomfort of the sole under the ball of the foot. Bars denote statistically significant differences ($p<0.05$)

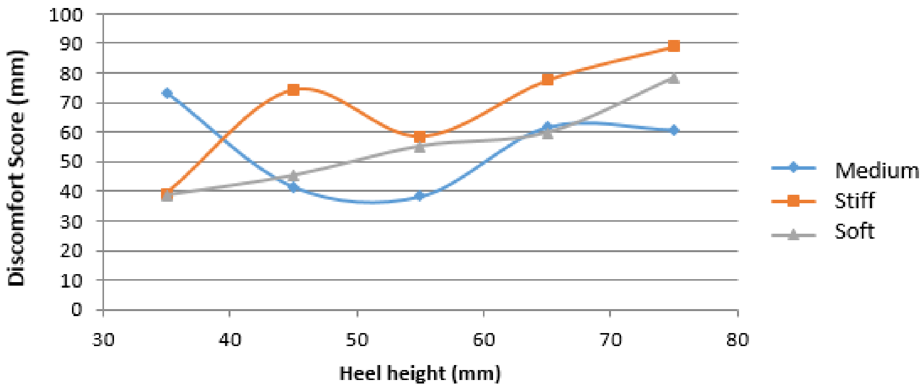

Figure 81: The interaction between heel height and material stiffness on discomfort of the sole under the ball of the foot

Under medial arch discomfort

The Mauchly's test showed that the data was spherical only for heel height ($X^2(9)=18.729$). The ANOVA test revealed that only the effect of heel height had a main effect on medial arch discomfort ($F(4,52)=12.101$, $p=0.000$). There was a significant increase in discomfort between the lowest heel height (35mm) and three of the four remaining shoes (55mm $p=0.019$, 65mm $p=0.032$, and 75mm $p=0.005$). The 75mm heel had significantly higher medial arch discomfort compared to 45mm ($p=0.005$, 44% change) and 55mm ($p=0.022$, 38% change). The results show that there is a clear effect due to heel height and the higher the heel the less comfortable the shoe.

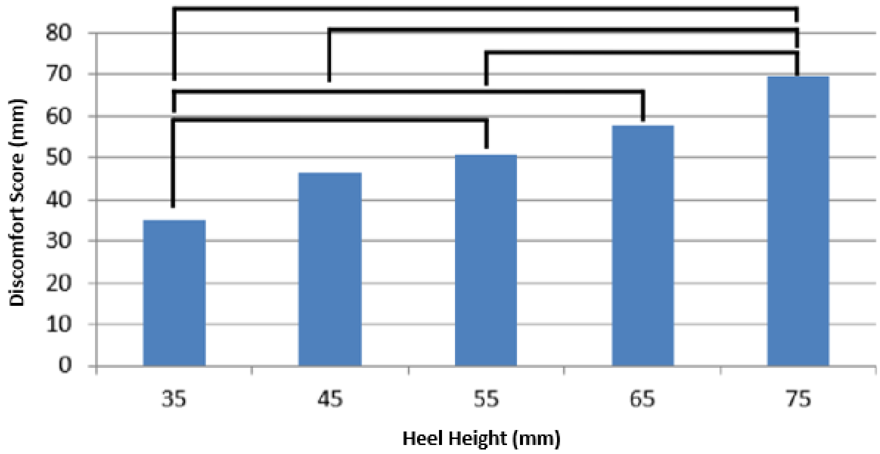

Figure 82: The effect of heel height on discomfort under the medial arch. Bars denote statistically significant differences (p<0.05)

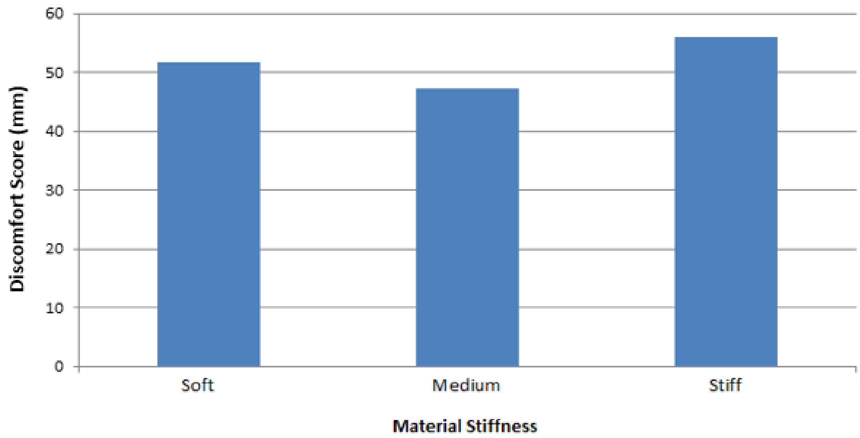

Figure 83: The effect of material stiffness on discomfort under the medial arch

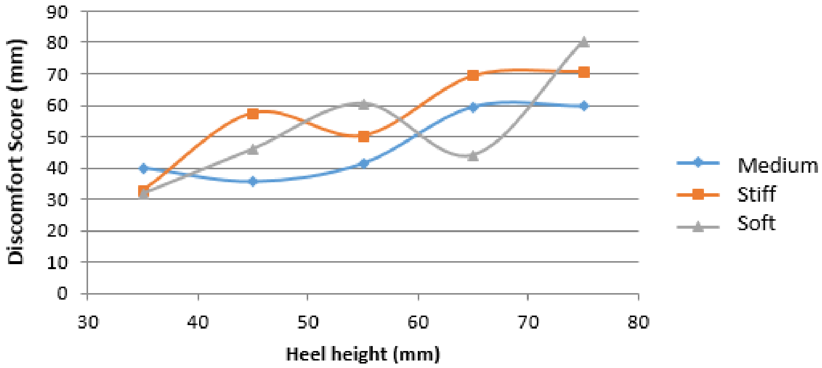

Figure 84: The interaction between heel height and material stiffness on discomfort under the medial arch

Toe related discomfort

The Mauchly's test showed that the data was only spherical for heel height ($X^2(9)=17.785$). The ANOVA test showed that both material stiffness ($F(1.864,24.226)=5.766$, $p=0.010$) and heel height ($F(4,52)=12.796$, $p=0.000$) had a significant main effect on toe comfort. The Bonferroni pairwise comparisons revealed that for heel height there were significant difference in toe comfort between the highest 75mm shoe and the 35mm ($p=0.006$, 113% change), 45mm ($p=0.010$), and 55mm ($p=0.004$, 50% change). There was also a significant difference between lowest 35mm heel and the 65mm heel ($p=0.024$, 80% change). There was also a significant difference in toe discomfort between the softest and stiffest materials ($p=0.018$, 32% increase). There was also a significant difference between the medium material and the stiffest material ($p=0.041$, 35% increase).

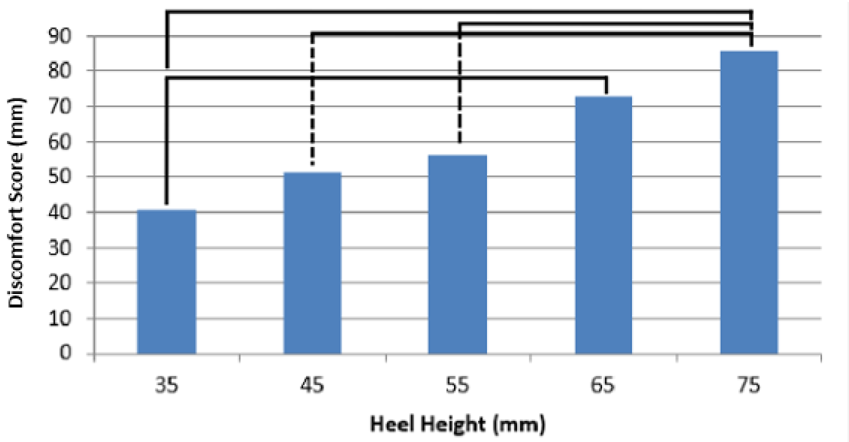

Figure 85: The effect of heel height on discomfort of the toes.
Bars denote statistically significant differences (p<0.05)

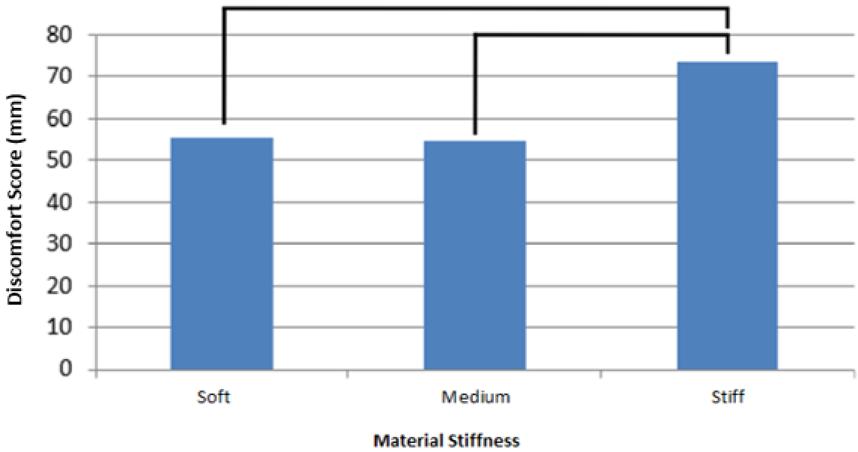

Figure 86: The effect of material stiffness on discomfort of the toes.
Bars denote statistically significant differences (p<0.05)

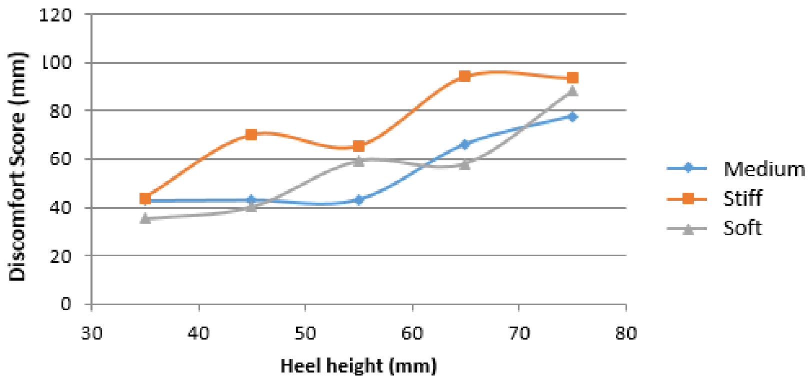

Figure 87: The interaction between heel height and material stiffness on discomfort of the toes

4.5.3. Fit

Measurements of the foot and last were taken and the differences between these dimension are shown in Table 11.

Table 11: The difference between the foot and last girths (mm)

	heel height (mm)				
Participant	**35**	**45**	**55**	**65**	**75**
1	-5	-6	-4.5	-1.7	-5.8
2	-7.2	-8.2	-6.7	-3.9	-8
3	3.7	2.7	4.2	7	2.9
4	-12.6	-13.6	-12.1	-9.3	-13.4
5	26.2	25.2	26.7	29.5	25.4
6	9.8	8.8	10.3	13.1	9
7	-14.1	-15.1	-13.6	-10.8	-14.9
8	-12.2	-13.2	-11.7	-8.9	-13
9	-6.1	-7.1	-5.6	-2.8	-6.9
10	-0.6	-1.6	-0.1	2.7	-1.4
11	-3.7	-4.7	-3.2	-0.4	-4.5
12	1.2	0.2	1.7	4.5	0.4
13	-5.3	-6.3	-4.8	-2	-6.1
14	-3.3	-4.3	-2.8	0	-4.1
15	-0.1	-1.1	0.4	3.2	-0.9
16	-6	-7	-5.5	-2.7	-6.8
Average	**-2.2**	**-3.2**	**-1.7**	**1.1**	**-3.0**
Standard Deviation	9.8	9.8	9.8	9.8	9.7

4.5.4. *Correlation between the fit (difference between foot and last) and discomfort*

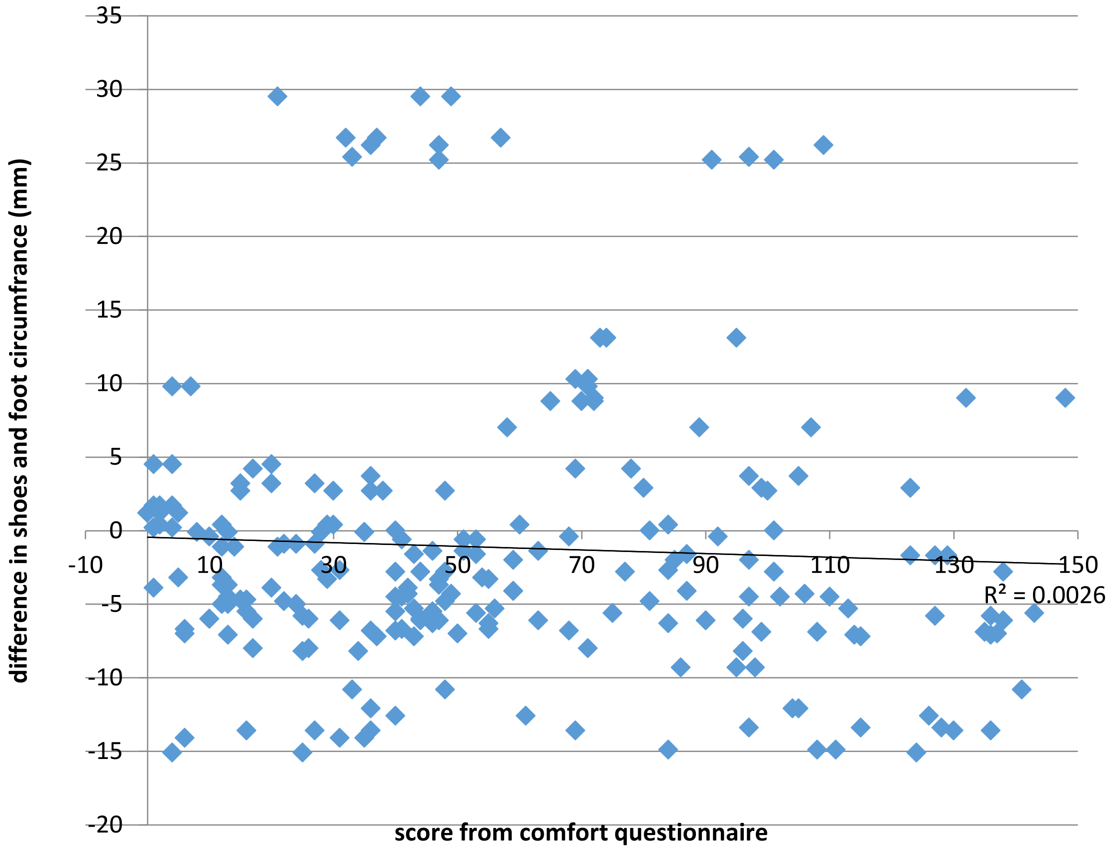

Figure 88: A comparison between the shoe/ foot circumference mismatch and the discomfort score attained for the overall discomfort question, across all heel heights (mm) used whilst wearing all the shoes. A higher discomfort score signifies reduced comfort

As can be seen in Figure 88 there is no correlation between the fit and the comfort score attained across all the footwear. Of the 50 Pearson's correlations only 6 were found to show a significant correlation between fit and one or more measures of shoe comfort (Table 12). Only the medium material produced significant results and the 55 and 75 heel heights produced a change in comfort in the most regions.

Table 12: The significant results from the Pearson's correlation tests, showing the relationship between the difference in shoe/foot volume and the comfort scores

Question asked	Heel height (mm)	Material stiffness	Pearson correlation	Significance
Overall width comfort	35	Medium	0.588	0.021
	55	Medium	0.661	0.007
Overall length comfort	45	Medium	0.634	0.011
	55	Medium	0.641	0.010
	75	Medium	0.620	0.018
Toes comfort	75	Medium	0.531	0.042

Due to the high number of tests completed an adjustment to the required significance value to 0.01 is often recommended. If such an adjustment was carried out only the overall comfort of medium material at 55mm heel height and overall length comfort of the medium material at 55mm heel height shoe, would have produced a significant result. With a limited number of significant results it appears there is little correlation between comfort and fit of these shoes.

4.5.3. Correlation between the tightness of laces and plantar pressure, the tightness of laces and comfort, and the difference in last and foot dimension and pressure.

There were no statistically significant correlations between the tightness of the laces and plantar pressures or between the tightness of laces and comfort. There were no statistically significant correlations between the difference in last and foot dimensions and plantar pressure.

4.5.4. Correlation between pressure and comfort

No significant correlations were found in any of these tests.

4.6. Discussion

4.6.1. Introduction

There were six primary aims to this study, the first three of which (1. effects of heel height, 2. effects of upper material stiffness and 3. their interactions) were further divided into two categories, (A) pressure and (B) comfort. The remaining aims focused on the interactions between the upper material stiffness and the heel height, plus the added effect of the tightness of the laces. The discussion is therefore divided into effects on pressure, effects on comfort, and effects due to lacing.

In many cases the results have shown there was a significant main effect but no significant effect was found in the pair-wise comparisons, this is because the Bonferroni correction used for the t-tests effectively multiplies the P value by the number of comparisons made. This is a harsh correction but is one that is widely accepted in the literature as the standard for these tests and similarly constructed studies have reported similar results [234]. Due to the Bonferroni being the accepted method and with no clear justification to use another correction these results were kept with the Bonferroni correction. Due to this, points will be discussed in detail for the significant pairwise comparisons found but also to a lesser extent the significant trends that were observed.

4.6.2. Effect of heel height and material stiffness on plantar pressure

This study found an increase in heel height transfers the pressure from the heel to the medial forefoot, which is consistent with previous studies [10, 23, 24, 39, 42, 44] and in agreement with hypothesis one. Furthermore, when heel height was increased the pressure at the forefoot increased for both MTP1 and MT24, which is consistent with most past studies [10, 23, 24, 39, 42, 44] but not all [152]. It was not possible to confirm if the pressure moved from the lateral to medial forefoot with increased heel height as suggested by others [34, 91, 109, 235] because some data values recorded at the lateral forefoot were less that the sensor operating range [200], thus hypothesis two could not be confirmed.

The results from this study support the past findings that when heel height is increased pressure reduces under the heel and increases under the forefoot [10, 23, 24, 39, 42, 44]. Past research has been unable to demonstrate much more other than this general relationship, therefore, it was not known by how much a heel height would need to increase in order to observe a significant increase in pressure. Nor was it known it the increases in pressure would be incremental as heel height increased, or whether, at a specific heel height, pressures start to exponentially elevate. This study has shown that an increase in heel height of 20mm between shoes is required to produce a statistically significant increase in pressure under the MTP1 region. Furthermore, when the heel height reaches 55mm an increase of only 10mm for this type of shoe is required to produce a statistically significant change in plantar pressure. However, this study also shows that the MT24 is less susceptible to changes in heel height and as a result very little increase in pressure is observed until the heel height surpasses 55mm. Since a change in the effect observed is seen after 55mm heel height, it could be suggested that shoes over 55m are defined as 'high heels'. These observations are similar to past work, which include a recommendation which states 'women should not wear heels of over 5.08cm [27]. Others have suggested that 'women are most inconvenienced by heels over 6cm [37]. The variation is most likely due to the variation between studies including the shoe design, the data being collected, and possibly the definition of heel height used. The proposal that a high heel is a shoe with an effective heel height of 55mm or more is also close to the initial definition adopted through the literature review.

There are a number of possible explanations why the pressure was reduced at the heel and increased under the ball of the foot. Firstly, the increased pressure at the forefoot is in part due to the reduced moment arm between the ankle joint and the centre of pressure. This is caused by the reduced distance between the heel and the metatarsal head as the heel height increases [67], an effect explained in chapter 2. This reduction in moment arm requires a greater force to be applied at the forefoot to maintain the same moment at the ankle that is required for ambulation. It has also been shown that wearing high heels causes greater deceleration of the centre of mass, to counteracted this effect an increased peak force is required to propel and accelerate the centre of mass forwards [51]. This increased propulsive force is produced during the push-off when the heel naturally begins to unload and therefore the increased force is focused on the forefoot, thus accounting for the increased pressure observed. Finally, the area of support in a high heel shoe is less than that in a low heel shoe due to the reduction in the length of the contact area [67] and the reduction of sole features that make contact with the ground [181]. This will increase pressure in the areas that remain in contact with the ground (since the loads are the same but shoe-ground contact area has reduced). This is further exacerbated because the forces have been redistributed onto the forefoot therefore the same forces are now distributed over a smaller foot-shoe contact area, increasing the pressure.

Despite the general agreement amongst studies that forefoot pressures increase, pressures under the hallux appear unaffected. Past studies consistently report an increase in pressure at the hallux when the height of the heel is increased [23, 39, 44]. Unlike the shoes worn in this investigation, all of the studies that showed an increase in pressure under the hallux, tested shoes that had a narrow toe box [23, 39, 44]. The increase in pressure under the hallux may therefore be characteristic of high heeled shoes in combination with a narrow toe box. Indeed, an increase in pressure at the hallux with a more pointed toe box has been reported [236]. One prior study supports this assumption [152] although they did not describe the shoe design investigated. They reported that a change in heel height from 12.7mm to 31.75 mm increased hallux pressure, although further increases from 31.75mm to 50.8mm reduced pressure. One implication of the data presented here and observations from prior research, is that that even when heel height in increased, changes in toe-box shape might be able to prevent further increases in hallux pressure.

An increase in upper material stiffness increases the pressure under the MTP1 and reduces pressure under the MT24, showing that hypothesis four must be rejected since it predicted a linear effect. As far as the author is aware this is the first time that the upper stiffness has been systematically increased across a group of shoes that are otherwise identical and therefore there is no past research to draw comparison with. The changes at MTP1 and MT24 occurred when the shoe was changed from the soft to the medium stiffness upper. The MTP1 is perhaps more susceptible to changes in material stiffness as it was the only region to change between medium and stiff upper. This may be explained by the proximity of the area to the sides of the shoe and therefore upper. Any effect on external load applied to the foot on the side of metatarsal one will directly affect this metatarsal, including the joint and the plantar loads at this site prior to having an impact upon MT2-4.

Increased pressure under MTP1 and reduction under MT24 could be indicative of a frontal plane arch of the forefoot. This would increase loads under MTP1 and MT5 due to increased upper stiffness resisting lateral movement of these structures. However, data for the latter is not available due to the values being outside the reliable range of the sensors. The concept of a frontal plane arch is a widely accepted feature of the foot anatomy [237]. Furthermore, the added compression between the bones that would be indicative of the arch feature, facilitated by the stiffer upper, might explain why conditions such as Morton's neuroma are associated with tight fitting forefoot areas [4].

The above findings for material stiffness are important, particularly for conditions such as metatarsalgia and perhaps Morton's metatarsalgia. Conditions such as these are thought to occur because of high compressive pressure between the metatarsals or under the metatarsals, leading to discomfort. Reducing upper material stiffness may be a simple but effective method of relieving pain or reducing the risk of these problems occurring or reoccurring. There are also implications for the design of footwear for people with diabetes. Shoes designed for those with diabetes try to move pressure away from areas at high risk of ulceration, such as metatarsal heads and hallux. The results here are evidence that the choice of upper material could be optimised to reduce the risk of pressure related plantar ulceration.

It was hypothesised that there would be a significant interaction between the effects of heel height and material stiffness on plantar pressure. However, despite observing significant effects due to both material stiffness and heel height there was no significant interaction found. The lack of interaction is likely because the material stiffness can only produce relatively small changes in pressure compared to heel height. If this is true then we would expect to see that larger changes to the shoe design such the shape of the toe box or a change in the volume available to the forefoot would show greater interaction with heel height. It may also be the case that, in order to reduce the effects of heel height multiple features of the shoe may need to be adjusted in unison in order to produce a sufficiently large effect to significantly interact with heel height.

4.6.3. Effect of heel height and material stiffness on comfort

There is a clear effect due to both material stiffness and heel height on the comfort of a shoe. An increase from 55mm to 75mm heel height results in a significant reduction of comfort in all regions except the dorsal surface and the sides of the metatarsal heads as shown in **Table 13**. An increase in heel height significantly reduces comfort on the plantar surface of the foot, including the forefoot, as proposed in hypothesis three. A significant result was also observed at the dorsal surface showing that an increase of heel height from 35mm to 75mm reduced comfort. The areas that were most susceptible to change in comfort due to changes in heel height were the overall length, medial arch and the toes. The comfort related to the sides of the metatarsal heads showed no significant changes in comfort due to changes in heel height. The comfort of the toe and the overall length are the most effected by an increased heel height. This is likely because, the foot slides forward in the shoe compressing the toes against the end of the toe box, giving the sensation that the shoe is too small. The reduced comfort at the arch is most likely due to the increased arch height that occurs when the foot is placed in an equine position, thus the arch is lifted from its base of support provided by the shoe. Similarly the increased arch height suggests that there is an increase in the loading of the internal structures of the foot in order to produce the increased arch height and this also could be the course of the increase in the sensation of discomfort.

Table 13: locations of discomfort and the percentage change in discomfort score between a 75m and 55mm heeled shoe

Location	**Increase in discomfort score between 55 and 75mm heel (%)**
Overall discomfort	64
Overall width	38
Overall length	59
Heel sole	35
Heel back	30
Ball of foot sole	50
Under the arch	38
toe	50

There is one shoe that consistently produces results that are not consistent with the other shoes. The stiff 55mm shoe often has much higher discomfort values than the other 55mm heeled shoes and often disturbs general trends that seem to occur. There is no clear reason for this but is perhaps because at this height the resistive nature of the stiff material produces the hindrance to the motion of the foot, which would also occur with higher heel heights but this negative quality is offset by the benefit of the stiff material holding the foot in the correct position when the shoe is higher. However, without further investigation it is not possible to conclude why this anomaly occurs.

Generally across all the questions asked, an increase in upper material stiffness reduced the comfort of the shoe as described in hypothesis 5. For all regions that had a significant difference between the medium and stiffest material there was also a significant difference between the softest and stiffest material but rarely was there a significant difference between the softest and medium. A possible explanation for this is once the material becomes quite soft the participant is unable to distinguish between two 'soft materials'. Also, whilst one material might be softer than another in terms of the extremes of their mechanical properties, in use whilst walking, they could be performing over a common range of stiffness. It may then be the case that the materials are not as distinct as first assumed.

When producing the shoes the manufacturer was requested to provide shoes that represented the stiffest and softest shoes they use and one that was 'in between' these extremes. The materials were therefore selected on pragmatic grounds and reflected real world practice and expectations of the materials. The investigator was provided with a stiff upper shoe made of bovine leather, a medium upper shoe made of bovine suede and a soft upper shoe made of goat suede. Leather is generally regarded as stiffer than suede and the difference in cell structure of the animal skin mean that goat suede is generally regarded as softer than bovine suede. Nonetheless to confirm the assumed distinct classification of the shoe leathers, samples of each upper material were taken directly from the shoes investigated (i.e. after the data was collected) and the material stiffness tested. Tests were carried out by independent footwear testing group INESCOP (Spain) and included: Determination of leather stiffness (ISO 5403-1:2011, clause 6.1), Determination of softness (ISO 17235:2011), and Tensile Strength (ISO 3376:2011). The results are shown in **Table 14**.

Table 14: The results of the material tests conducted by INESCOP, Spain

Test Conducted	**Goat Suede (soft upper)**		**Bovine Suede (medium stiffness)**		**Bovine Leather (Stiff upper)**	
	right	left	right	left	right	left
2mm compression	2	1.7	1.7	2	6.6	7.2
4mm compression	2.1	1.7	2	2.2	6.4	7.2
6mm compression	2	1.8	2.2	2.3	6.5	7.4
mean	1.88		2.07		6.88	
Softness * (mm distension)						
	6.4	7	6.4	7	4.6	4.3
	6.6	6.8	6	7	4.5	4.3
	7	7	6.5	6.5	4.5	4.1
mean	6.80		6.56		4.38	
Tensile Strength (N/mm^2)	20.6	13.8	25.4	19.8	18.5	19.5
Elongation at break (%)	59	62	57	49	51	39
Thickness (mm)	1.32	1.4	1.47	1.53	1.41	1.5

It is clear that there is little difference between the Bovine Suede and the Goat Suede (i.e. medium and soft materials in the study). In particular the test of leather stiffness reveals only a very small difference between the goat suede (2.0N) and the Bovine suede (2.2N) for a 6mm compression of the material, whilst the Bovine leather is more than three times greater (6.5N). However, this is a measure of the compressibility of the material and this is perhaps not a characteristic that footwear wearers mean when they describe the upper as ‘stiff’. Nor is compressive stiffness the material quality usually expected to affect the constraint of the forefoot inside the shoe. A description of a stiff upper usually infers that the upper does not deform to the shape of the foot very easily, this would be more accurately described by the young's modulus. A more detailed discussion on the implication of these tests is presented in chapter 6. However, they clearly identify that the three materials did not represent three distinct materials whose properties were different from each other to a consistent degree. This could perhaps explain why the comfort data rarely showed significant differences between the soft and medium stiffness materials yet many differences between the medium and the stiff uppers.

4.6.4. The correlation between fit (difference between foot and last) and comfort

As can be seen in Figure 88 there is no correlation between the fit and the comfort score attained across all the footwear. However, within that data set there are a number of variables that may be masking possible trends in the data, for example participants with a narrow foot may have preferred a close fit when the shoe is low heeled but a loose fit when the shoe is high heeled. To overcome this more detailed scrutiny was carried out on the data to find possible trends. The Pearson's correlations were tested on all of the questions asked in the questionnaire for each heel height and material stiffness. Of the 50 Pearson's correlations, 6 were found to show a significant correlation between fit and one or more measures of shoe comfort (Table 12), such a small number of significant cases does suggest that these are simply random significant results that have occurred because there were so many tests conducted. However, contrary to this fact the significant P value reported is often very low and in one case as low as $P=0.007$ (overall width comfort question when wearing the medium material shoe with a 55mm heeled). Furthermore, all the significant cases occurred in the medium material suggesting that fit only has an effect on comfort when the upper is of medium stiffness. Due to the high number of significant tests required it is recommended that future research conducts this test with fewer shoes but a greater number of participants to ensure that more robust statistics can be conducted.

4.6.5. The repeat trials of the control shoe

For both the comfort and plantar pressure tests, significant results were found when comparing the data collected from repeated trials of the control shoe. In all cases these occur between the first trial and either the 2^{nd} or 3^{rd} trial, but never 2^{nd} and 3^{rd} trials. When completing the questionnaire for the first control shoe, the participant is completing the questionnaire for the first time. It is possible that the significant differences observed are due to a learning effect whereby the second and third occasions provide more stable data as the concept of comfort due to the participant having worn more shoes. If this is the case then the non-control shoes collected in the data collection may have experienced the same but reduced effect. However, this will have limited effect of the overall results since the non-control shoes were given to the participants in a random order. Since the data from the first control trial may not be reliable when comparison of the medium stiffness 55mm heel was required the second data set was used, which was never statistically different from the third data set.

4.6.6. The effect of Lacing and fit correlations on pressure and comfort:

Many correlation tests were carried out in order to investigate if there were any possible associations between forefoot fit, lacing, comfort and pressure. Correlation tests investigated potential correlations between (1) comfort and the tightness of lacing, (2) pressure and the tightness of lacing, (3) comfort and the difference in foot and last circumference at the forefoot (forefoot fit), and (4) pressure and forefoot fit (5) comfort and pressure. Of all the tests carried out none were found to be significant and it is therefore apparent that the small differences in fit due to the differing foot sizes have no significant effect on pressure and comfort. Despite these findings not being significant, it is still possible that there is an effect due to both foot size and lacing. Foot size is extremely variable whilst, only few measurements were observed in this investigation many more exist and thus it is possible one not investigated here would have had a significant result. It is also clear that there was relatively high variability between participants and the low number of participants in the study, thus a higher number of participants may have produced a significant result. The measurement of the distance between the eyelets of the laces may have actually been the wrong measurement of the laces to take. Since the width of the eyelets is not an exact measure of tightness because each person's foot is a different size and shape. A person with a larger foot may have therefore had a larger distance between the eyelets but the shoe was the same tightness. A better measurement may have been to measure the tension of the laces instead.

4.7. Limitations

4.7.1. Medial-lateral heel wedging

Past research has suggested that a reduced base of support increases instability during gait [238]. It is then reasonable to suspect that plantar pressure distribution will also change when the base of support is reduced. This may be due to a gait adaptation which compensates for the increased instability. To prevent the base of support being part of the independent variable within this investigation the manufacturer was asked to produce all the shoes with the same width of heel. Despite this, the manufacturer kept the heel wedge angle the same meaning that the width of the heel's contact area decreased as heel height increased. There was a 20mm or 33% reduction in sole width at the heel between the lowest to the highest heeled shoe. Whilst it is possible that there was an effect on the pressure recorded due to the reduction in heel width, the overall effect of this is expected to be much less than that which can be attributed to heel height, especially since, the footbed had the same dimensions in the heel region for all shoes.

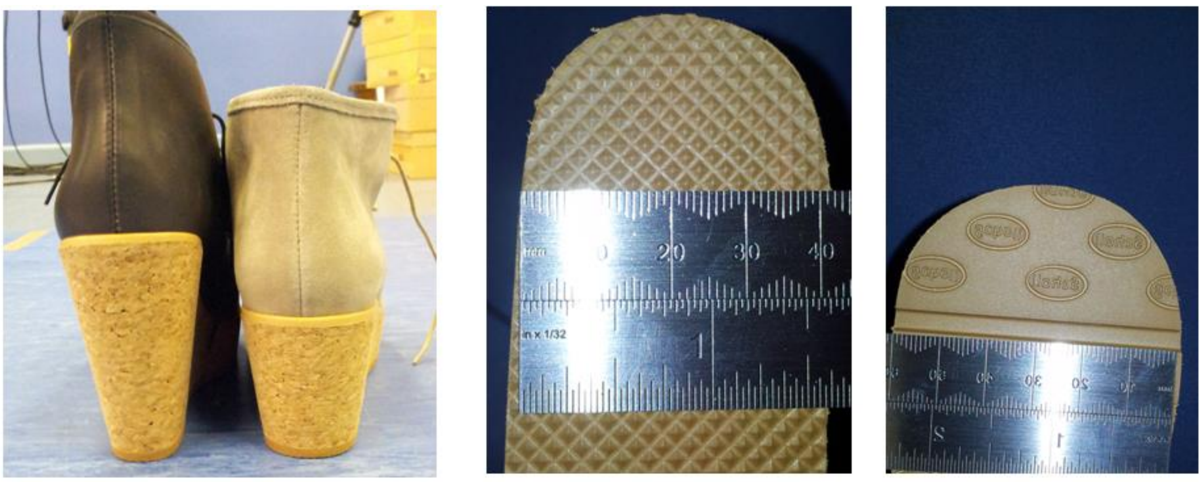

Figure 89: The difference in the heel base of supports

4.7.2. Materials used

There was very little difference in the material stiffness of soft and medium stiffness shoe (**Table 14**). Perhaps if the shoes used had a more extreme difference in material stiffness a clearer result would have been found. The material chosen for this study were natural hides. Using materials of this kind makes it hard to control properties such as tensile strength. This study used materials that are commonly used in the footwear industry and that were supposed to represent those that are commonly available. However, the medium and soft uppers were not as distinct from each other as the medium and stiff uppers, which has limited the development of a clear understanding of the wider relationships between stiffness, pressure, and comfort. However, it is reassuring that the pressure and comfort results from the materials that were very similar produce similar results, as this provides us with confidence that the measures were robust.

4.7.3. Heel seat

Past research has shown that heel seat angle and heel seat length can affect comfort [36]. However, when heel height is increased the heel seat angle or wedge angle has to change in order to accommodate the foot. Thus, like previous studies, this investigation used adjustments to the heel seat where which were recommended by the last maker. There are recommendations and an equation that links heel elevation, heel height, and wedge angle that is outlined in Goonetilleke 2012 [38]. Whilst no data has been found that shows the effect of the heel seat length and heel wedge angle on plantar pressure, research has shown that for a fixed heel seat length of 45mm with a heel of 25mm and a heel wedge angle of 5^{o}, the highest comfort score was achieved. The lowest score found was observed when the heel height was 75mm and the heel wedge angle was 22^{o}. These two extreme cases produced a range in the comfort score from 31.1 to 65.3, a difference of 34.2 of a possible 100. However, when the heel height was fixed but the wedge angle was changed the comfort score given had a range of 32.9, of the possible 100, when the wedge angle was changed over a range between 0 – 10^{o} [36]. It is therefore clear that heel wedge angle can have an effect on comfort in much the same range as that of heel height and therefore to a greater effect than material stiffness. Unfortunately, Goonetilleke 2012 [38] was published after the shoes for this study were ordered and therefore the values used in this study were those used by the manufacturer.

4.8. Conclusion

This investigation revealed that with an increase in heel height the peak pressure moves from the heel to the medial forefoot. In order to produce a significant change in pressure at the MTP1 region in low heels, a height increase of 20mm is required. In shoes with a heel over 55mm a height increase of only 10mm is required. Building on the evidence from prior studies [27, 239], it is therefore proposed that, for plantar pressure investigations, shoes with greater than 55mm effective heel height should be regarded as different to shoes that have a heel lower than 55mm. thus it follows that if a difference in heel height of 20mm is required between shoes to see a significant effect then a low heel shoe should never have an effective heel height of more than 35mm. defining low heel shoes as below 35mm is further supported by previous work that has shown heels of 38mm increase the varus moment at the knee [64]

These results could be of particular importance to a designer, since previous studies have never reported the range within which a designer can change a shoe before pressure is increased. Prior to this study designers may have been apprehensive when changing the heel height of a shoe. With the results from this study designers now know that they can make relatively large changes when the shoe is low (below 55mm) and some changes are still possible when the shoe is high (above 55mm), without significantly effecting pressure.

This study also tested the effects of upper material stiffness on plantar pressure. Post study testing of the footwear used revealed that whilst three upper materials were tested, that two had very similar mechanical properties **Table 14**. Regardless, it was found that an increase in material stiffness increased the pressure under the MTP1 whilst reducing it under the MT24. To the authors knowledge this is the first reported case of such an effect and reveals the potential for upper designs to be adjusted in order to optimise pressure distribution. This study failed to observe any significant change in hallux pressures when upper stiffness was varied.

Chapter 5: An Investigation into the Effects of Shoe Volume and Upper Stiffness in High Heeled Shoes on Plantar Pressure and Comfort.

Chapter 5 Introductory outline:

The aim of this chapter is to further investigate the effects of shoe upper parameters in high heeled shoes on plantar pressure and comfort. The previous chapter investigated the effects of upper material stiffness across a range of heel heights. Building on the outcomes, the work in chapter 5 will investigate how the volume of the shoe in the forefoot area affects plantar pressure and comfort and whether upper material stiffness interacts with any effect.

5.1. Introduction:

In previous chapters, it was explained that a shoe can be considered to have a "high heel" if it raises the heel of the foot above the forefoot by 55cm or more. Chapter 2 was concerned with looking closely at the anatomy of a shoe and considered how a given feature may affect the wearer. In high heeled shoes there are a number of features that are common to the style category, such as narrow or pointed toe boxes, nominal or no arch support and a reduced contact area between the shoe and the ground. Many of these features may have a detrimental effect on plantar pressure distribution and comfort. One such feature is the reduced volume inside the shoe. A reduced volume is often due to a shallow (distance from footbed to the upper), narrow (medial-lateral distance), and pointed toe box. Another important feature is the material used for the upper in particular the stiffness of the upper material. Together the shoe volume and upper stiffness affect the ability of the upper to deform when contacted by the foot and loads applied to the upper by the foot. It has been stated that the definition of footwear fit is the functional geometrical match of the foot and shoe, which can be assessed objectively via geometric and biomechanical measurements and subjectively via perception measurements [123]. Thus, it is reasonable to assume that both the internal volume of a shoe and the material stiffness of the upper will both influence the fit of the shoe and the experience of the wearer.

There are two primary characteristics of a shoe that affect the amount of volume (space) inside the shoe that is available to the foot. The first is the internal dimensions of the shoe which are a result of the shoe last shape and the insoles fitted as the footbed on top of the shoe sole. The second is the stiffness of the materials that make up the shoe, including the stiffness of the upper. Whilst, some manufacturers change the dimensions of the shoe last dependent upon upper material, others do not, perhaps suggesting there is no objective understanding of when and how to change uppers when last shape is altered. Currently no research has been reported that investigates the interaction between shoe volume and upper material stiffness.

Two of the shoe dimensions often changed are the medial, and lateral forefoot angles, which along with the length of toe allowance, define the shape of the toe box. The toe box shape and subsequently the limited amount of space the shoe provides for the toes has been blamed for the discomfort and some of the health risks associated with wearing high heeled shoes [92].

Comfort of footwear and the health of the wearer have a clear relationship [16, 220]. In high heels the fit of the forefoot including the shape of the toe box is often blamed for poor foot health and therefore it is imperative that the current understanding of comfort when wearing high heels is improved to reduce the risk to wearers. Specifically, to improve comfort and reduce health risks there is a need for a better understanding of the effects of variations in fit (i.e. foot shape vs shoe shape and volume, and upper stiffness) in the forefoot region of high heeled shoes. Currently it is not known how the relationship between forefoot shape and shoe shape affect comfort and plantar pressure, nor how upper material stiffness affects this. It is therefore important to increase our knowledge on the relationships between forefoot shoe volume, material stiffness, plantar pressure, and shoe comfort so that potential health risks can be identified and simple design requirements can be stipulated in order to improve the health of the high heel wearer.

5.1.2. Aims

There are four primary aims to this investigation:

1. To identify the effects of reduced shoe volume on (A) plantar pressure and (B) comfort.
2. To identify the effects of increased upper material stiffness on (A) plantar pressure and (B) comfort.
3. To investigate if an interaction exists between the effects of upper material stiffness and shoe volume on (A) plantar pressure and (B) comfort.
4. To investigate any correlation between the difference in the shoe - foot dimensions and comfort.

From these aims it is possible to propose a number of hypotheses:

1. Plantar pressure under the medial forefoot will increase with reduced shoe volume
2. Plantar pressure under the lateral forefoot will reduce with reduced shoe volume
3. Comfort will reduce under the forefoot with reduced shoe volume
4. Plantar pressure will increase under the MTP1 and decrease under the MT24 with increased material stiffness.
5. Comfort will reduce under the forefoot with increased material stiffness.
6. A decrease in the difference between the volume of the shoe and the foot will produce a reduction in the comfort reported

5.2. Methodology

5.2.1. Participants

The 20 participants for this study were recruited from the student and staff populations of the University of Salford and the staff population of Reckitt Benckiser Group plc. Recruitment was conducted via email and posters.

The inclusion criteria were: female (due to shoe style), aged between 18 and 45, and able to walk unaided for 1.5 hours. The participants also had to able to understand both written and spoken English to ensure that the participants understood what was asked of them and their rights as a participant. The exclusion criteria included: any known foot or lower limb injuries or visible abnormalities such as musculoskeletal disorders including diabetes, neuropathy, and rheumatoid arthritis.

5.2.2. Instrumentation

5.2.2.1. Measurement of Comfort

A comfort questionnaire using a Visual Analogue Scale for each specific region of the foot was completed by each of the participants whilst wearing each shoe. The questionnaire is identical to that used in chapter 4.

5.2.2.2. Measurement of plantar pressure

In-shoe plantar pressure was recorded using Pedar-X system (Novel GMbH, Munich, Germany). The insoles were placed in the shoes between the sock and shoe insert. The

Pedar insoles were connected to the data logger that was attached to the participant via a waist belt. From the data logger the data was transmitted to a laptop computer wirelessly via Bluetooth. A more detailed description of Pedar was provided in chapter 2 and 3, including how best to collect data and when values should not be accepted due to the limitations of the system, these recommendations were be adhered to throughout this chapter.

5.2.2.3. Measurement of foot shape

The 3D shape of the foot was measured to allow the relationship between it and the last (i.e. the internal shape of the shoe) shape to be quantified. Each participant had their foot shape measured using a 3D Foot Scanner (Icad PIE, INESCOP, Spain). The foot was placed flat on the glass platform within the scanner whilst the participant stood relaxed. The other foot was on an adjacent platform at the same height as the foot being scanned.

A 3D foot scanner (Icad PIE, INESCOP, Spain) provided 3D foot shape data. To do this the scanner emits a line of infra-red dot lasers which are subsequently detected by receivers. The time lag between light emission and the subsequent reception enables the device to perform a line of measurements on the foot surface. This process is repeated at 1 mm intervals along the foot. Once the scanner has traversed the length of the foot, all the measurements taken are represented as a point cloud. From the point cloud a mesh can be made from which measurements can be taken with the accompanying software. Once a foot scan is taken, the image is filtered to remove noise due to ambient light. Any further noise was removed manually on screen. The point cloud was then exported to Rhinoceros

3D software as a mesh (McNeel North America, Seattle, WA, USA), and the INFOHORMA (INESCOPE, Spain) plug-in software used to take specific foot shape measurements. These would later be compared to footwear last shape data collected using the same method.

There are some measurements that are believed to be good representation of foot shape and are commonly used in the foot health sector, such as navicular height divided by foot length which is called the arch index and used as a predictor of arch height [232]. Other measurements include: Navicular height (distance between the navicular tuberosity (NT) and the ground), navicular width (distance between the NT and the foot midline (the foot's long axis), navicular distance; (distance between the NT and the pterion); big toe height; and big toe width. Many of these same measurements are also used by the scanner's software in order to orientate the foot, however, the scanner is unable to measure navicular height and related measures. Therefore, in order to get the best results the manufacture recommends the user takes these measurements by hand.

5.2.2.5. Walking speed

Two Brower tc-timing system light gates (Brower Timing Systems, Draper, Utah, USA) were positioned 12 meters apart and used to measure walking speed. There was a further 3.5 meters before and after the timing gates to allow acceleration and deceleration areas either side of the area where measurements would occur.

5.2.3. Footwear

The shoes used in this study were made of 3 different uppers, in order of stiffness from least to most, they were: bovine suede, goat leather and bovine leather *(the outcomes of the upper material stiffness testing detailed in chapter 4 were not known at the time of designing and implementing this study).* All footwear were based on the same design and were made from identical lasts, soles and heel pieces. The upper materials were therefore the primary independent variable. The design chosen included a rounded toe box in an attempt to ensure that any effect of toe box narrowing did not interact with the variations in upper materials.

Two shoe sizes were used (UK 5 & 6) and all shoes had a 60mm heel and a 5mm sole in the forefoot, giving a 55mm effective heel height. This height was chosen as it represents the lowest height at which there was a clear effect due to heel height and therefore the shoe can be considered a high heeled shoe (established in chapter 4). A shoe design that included laces was chosen to allow easy fitting. The two leather materials were both black to prevent aesthetics affecting the perceptions of comfort. However, the suede shoe was brown and due to the clear difference in the feel and texture of the material, aesthetic differences between the shoes were inevitable. This was assumed to have minimal effect since past research in similar footwear has shown there to be no statistically significant influence of aesthetics on comfort measures [21].

Figure 90: The shoes used:
Top left, bovine suede; top right, bovine leather; bottom left, goat leather

5.2.4. The insoles

Insoles were used to reduce the volume of space inside the shoes. There were three internal shoe volume conditions which were: no insole, thin insole and thick insole, which produce the largest, medium, and smallest volumes respectively. The shapes of the insoles matched the internal shape of the shoes and were produced using the last bottom outline provided by the manufacturer. The insoles consisted of two (thin insole) or three (thick insole) layers.

In the no insole condition the participant wore the shoe alone with the shoes own insole inside (that could not be removed). This was the largest volume condition. For the medium volume condition, the thin insole was inserted. This comprised a 3mm Poron layer with 1.4mm leather board (Algeos) beneath, which was placed on top of the insole already inside the shoe. For the smallest volume condition, two 1.4mm layers of leather board (i.e. 2.8mm in total) were added beneath a 3mm layer of Poron.

The purpose of the Poron layer was to provide a comfortable surface for the foot when walking on top of the leather board. It was assumed that the Poron fully compressed in both medium and smallest volume conditions and thus the net change in shoe volume was due entirely to the leather board layer (1.4mm and 2.8mm). The leather board was therefore used to systematically reduce space inside the shoe in 1.4mm increments. It was chosen because it is very stiff under compression and therefore the loss in volume would be consistent across individuals. However, as thickness of the leather board increases from 1.4 to 2.8mm the resistance of the thicker insole to toe flexion should ideally remain the same as the 1.4mm condition, since this might affect foot biomechanics and therefore plantar pressures and comfort. To keep the resistance to flexion consistent between the 1.4mm and 2.8mm conditions, the second layer of leather board was cut into multiple sections and glued to the underside of the unbroken layer of leather board (Figure 91). This provided almost no change in resistance to flexion and kept resistance to flexion consistent between the thin and thick insole conditions.

Figure 91: layers of the insoles

5.2.5. Testing Procedure

All testing was carried out at the University of Salford in the Brian Blatchford gait lab or the head office of Reckitt Benckiser Group plc (Dansom Ln, Hull, UK). Both rooms are secluded and without windows, thus there is very little that can distract the participant or inhibit them whilst they walk.

Participants had received written information prior to arrival as part of initial screening. On arrival the participants were welcomed and an explanation of the testing procedure was given, along with a written procedure. The participant was reminded that they did not have to take part and they were free to stop participation whenever they chose. When the participant was happy they were asked to provide signed consent.

The order in which shoes were tested was randomised using a Matlab script. However, the medium upper stiffness and large volume shoe was used as the control (repeated measures) shoe and tested first, 6^{th} and last. The purpose of repeating this shoe was to evaluate if participants were consistent in their scoring of the VAS scale throughout the testing process.

The participants were asked to remove their shoes and socks and given a pair of nylon socks to wear. Following this initial process the participants were given the first test shoe and asked to fit the shoe comfortably. They were then given a period to acclimatise to the shoes and the required walking speed. This consisted of walking laps of the test area whilst practicing the correct walking speed. The total time the participant was wearing the shoes prior to collecting data exceeded the 166 minimum step recommendation developed in the previous methodological study (Chapter 3). Following this the shoe trial began and the Pedar in shoe pressure data was collected. This process was then repeated for all 11 conditions (nine shoe material/volume conditions and the control shoe repeated two further times).

The foot measurements were taken after the shoe trials. This included both the scans of the feet and the measurements taken by hand.

5.2. Data processing

As discussed in the previous chapter 'masks' identifying anatomical regions of interest are often used when investigating plantar pressure. In the previous chapter the development of a mask suitable for this thesis was also discussed and the data for this study was processed using the same masks. Plantar pressure data was therefore derived for the following regions: 1st metatarsophalangeal joint (MTP1), 2nd–4th metatarsophalangeal joints (MT24), the hallux, 5th metatarsophalangeal (MT5), the heel, and the midfoot.

More steps were required for data collection than what was required to walk one length of the test area. This was due to the limited dimensions of the gait lab. As a result the participant had to walk numerous lengths of the test area until sufficient steps had been collected. The consequence of this was undesired steps in the data set which were collected whilst the participant was accelerating, decelerating, or turning at each end of the collection area. These undesired steps were clearly visible in the data because the participant was asked to stop before they turned at each end of the lab. MATLAB code was written that enabled the investigator to remove steps during which the participant was accelerating, decelerating or stood/turning. In addition, at least one step per foot before and after the acceleration/declaration/stop period was removed so as to minimise the risk of none walking footsteps being included. The same investigator processed all the data. Thirty acceptable left foot steps were collected and the plantar pressure values from each individual sensor were averaged to produce an average step for each participant in each shoe condition.

In order to compare the difference in foot and last volume, so that fit could be quantified, a method of comparing the last dimensions to the foot dimensions was required. A method of doing this was established in chapter 4 and was used again in this investigation. This consisted of scanning both the foot and last to measure the girths at 65% of foot length, with a ball angle of 12^{o}, and an inclination angle of 21.4^{o}. The difference between the last and foot girths could then be found by subtracting foot values from last values and thus negative values indicate that the foot is larger than the last.

5.3. Statistical analysis

The statistics for this study were completed in SPSS statistics (v.20) software package. A within-within (two way) ANOVA design, with repeated measures was used to establish the effects of forefoot volume (research aim 1A) and material stiffness (research aim 2A) on plantar pressure. For each of the separate anatomical regions defined a separate ANOVA test was conducted. The significance level for each of these tests was set at p=0.05 and an adjustment using Bonferroni correction was used for multiple comparisons. This process was then repeated for data taken from the comfort questionnaires. These tests were used to establish the effects of forefoot volume (research aim 1B) and material stiffness (research aim 2B) on comfort. The ANOVA tests were also used to test for an interaction between the forefoot volume and material stiffness on plantar pressure (research aim 3A) and comfort (research aim 3B).

To establish if forefoot fit (research aim 4) can affect any effects observed in the comfort data, Pearson's correlation was used between forefoot fit data and every comfort score individually for each participant. Correlation was deemed statistically significant at the 0.05 level (2-tailed).

5.4. Results

5.4.1. The Effects on Plantar Pressure of Changing the Volume of the Shoe and the Upper Material Stiffness.

When shoe volume was increased independent of material stiffness, plantar pressure increased by 12% under the MTP1 and reduced by 8% under the heel. Under the MT24 the shoe with medium volume produced the lowest plantar pressure and thus unlike the MTP1 the effect was not linear as volume increased. Increasing material stiffness independent of volume reduced the plantar pressure under MTP1 and increased plantar pressure under MT24.

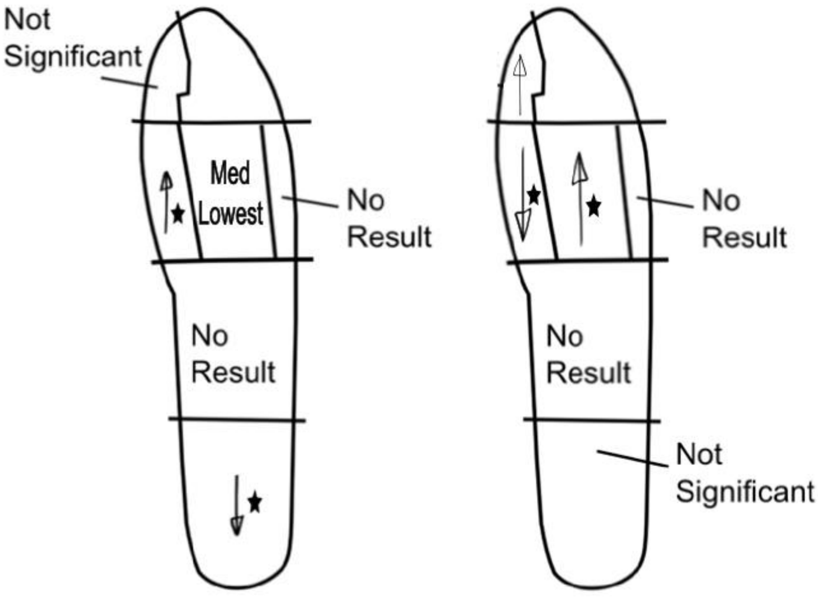

Figure 92: left: The Effects of Increased Volume
Right: The Effects of Increased Stiffness. An upwards arrow shows an increase in plantar pressure, downwards arrow shows reduction in plantar pressure, 'med lowest' shows that the medium upper shoe had the lowest plantar pressure, and a star shows that there was a statistically significant pairwise comparison

MTP1

Plantar pressure under the MTP1 is reduced when the shoe material stiffness is increased (5% reduction from soft to stiff upper shoe) and when volume is reduced (12% reduction from largest to smallest). Whilst it is apparent from Figure 93 that there is a gradual reduction in plantar pressure coinciding with the increased upper stiffness, there is only a statistically significant reduction between the softest and stiffest conditions. For shoe volume, the largest volume had a significantly greater plantar pressure value compared to both the reduced volume conditions.

In terms of any interaction between volume and upper stiffness, the largest volume combined with the softest upper material produced the highest plantar pressure at MTP1. There is a general trend of reducing plantar pressures with smaller volumes and stiffer uppers, and the smallest volume and stiffest material produce the lowest plantar pressure under the MTP1.

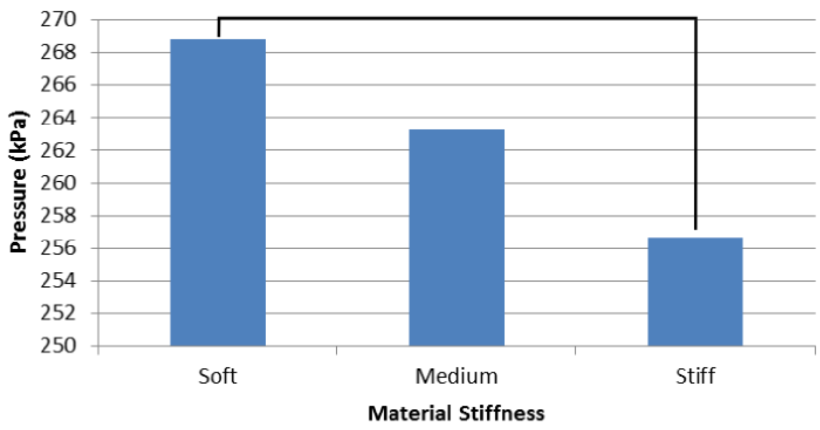

Figure 93: The Effects due to material stiffness on Plantar Pressure under MTP1

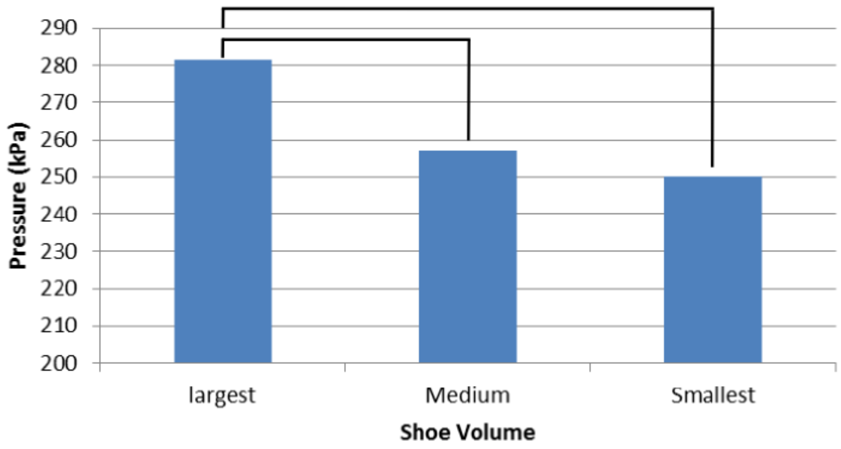

Figure 94: The Effects due to shoe volume on Plantar Pressure under MTP1

Mauchly's test show that the data is spherical for material stiffness ($X^2(2) = 0.587$), volume ($X^2(2) = 2.999$) and the comparison of both volume and stiffness ($X^2(9) = 9.670$). From the ANOVA results it is clear that there is a statistically significant main effect due to the material stiffness ($F(2, 44)=6.743$ $p=0.003$). There is also a statistically significant main effect due to shoe volume ($F(2,44)=21.72$ $p=0.000$), where a reduction in shoe volume reduced MTP1 plantar pressure. A statistically significant interaction between shoe volume and material stiffness ($F(4,88) = 3.022$ $p=0.022$) was observed. This interaction reveals that values for the soft upper shoes are statistically significantly different to the stiffest shoes ($p=0.006$). Whilst interactions between the volume data revealed that values obtained for the smallest volume are statistically significantly different to the medium ($p=0.000$) and the largest volume (p=0.000) shoes, there is no statistically significant difference between the medium and the largest volume shoe.

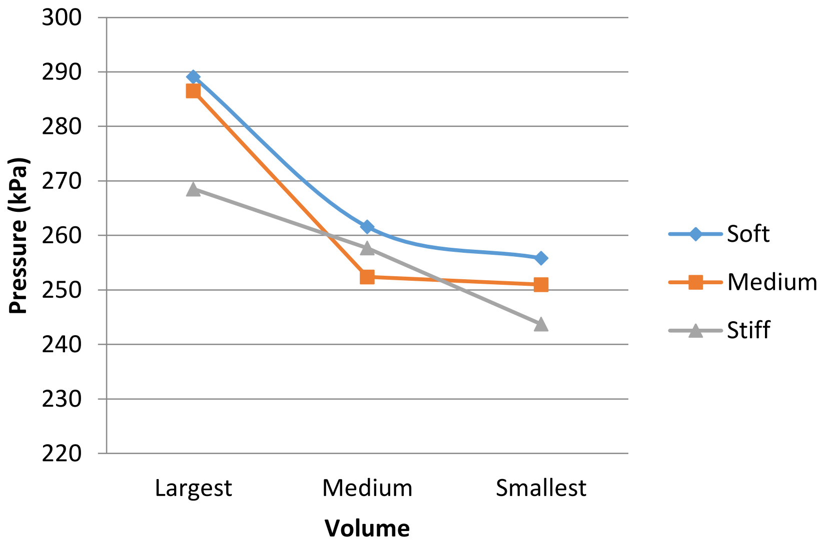

Figure 95: The interaction between Volume and Shoe Stiffness and their effect on Plantar Pressure under MTP1

MT24

In contrast to the MTP1, the MT24 has statistically significantly lower plantar pressure for the softest upper material compared to the stiffest upper (5% lower). Similar to the MTP1, the MT24 shows that as stiffness is increased plantar pressure increases, although, there is only a statistically significant difference between the soft and the stiff conditions. In this case the lowest plantar pressure value is that of the medium volume (11% reduction from largest to medium volume).

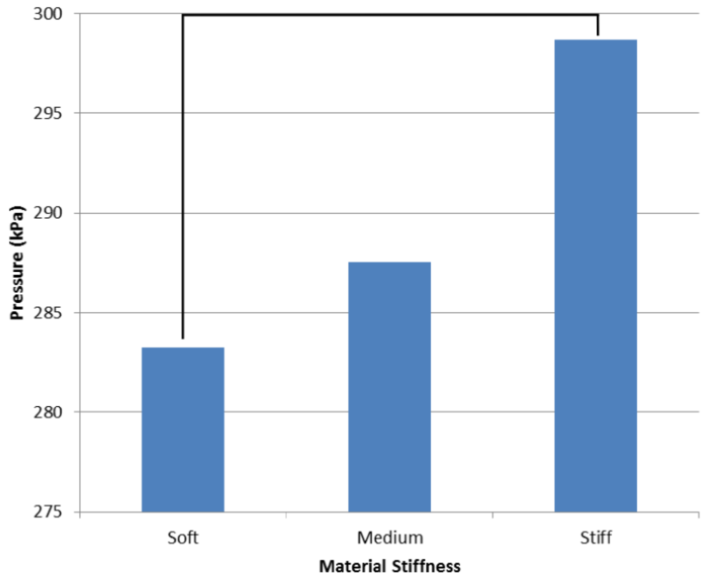

Figure 96: The Effects due to material stiffness on plantar pressure under MT24

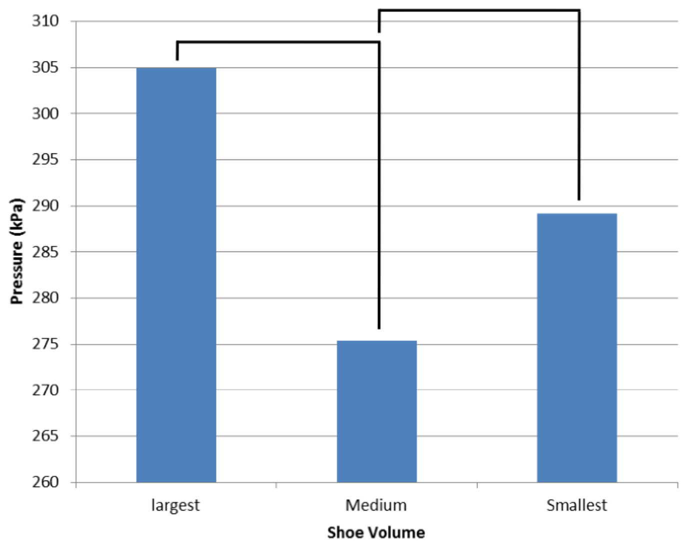

Figure 97: The Effects due to shoe volume on plantar pressure under the MT24

Mauchly's test show that the data is not spherical for material stiffness ($X^2(2)$ = 7.429), volume ($X^2(2)$ = 20.876) or the comparison of material stiffness and volume ($X^2(9)$ = 60.657). From the ANOVA results it is clear that there was a statistically significant effect due to material stiffness (F(1.554,35.753)=5.821,p=0.011). Shoe volume also produced a statistically significant effect (F(1.240,28.521)=9.730, p=0.002), with a reduction in shoe volume reducing the MT24 plantar pressure. However, as can be seen from Figure 97 this is not a linear trend from largest to smallest volume. The largest volume condition has the highest recorded plantar pressure and it is the medium volume condition that has the lowest value. Changing the volume above or below that of the medium upper shoe resulted in an increase in plantar pressure at MT24. There is also a statistically significant interaction between shoe volume and material stiffness (F(1.694,38.953)= 4.335 p=0.025). From the Benferroni pairwise comparison it is evident that there is a statistically significant increase from the soft to the stiff material (p=0.033, 5% increase). There is also a statistically significant reduction in MT24 plantar pressure between the smallest and medium volume shoes (p= 0.001, 5% reduction), and statistically significant increase in MT24 plantar pressures from medium to largest volume shoes (p=0.002, 11% increase).

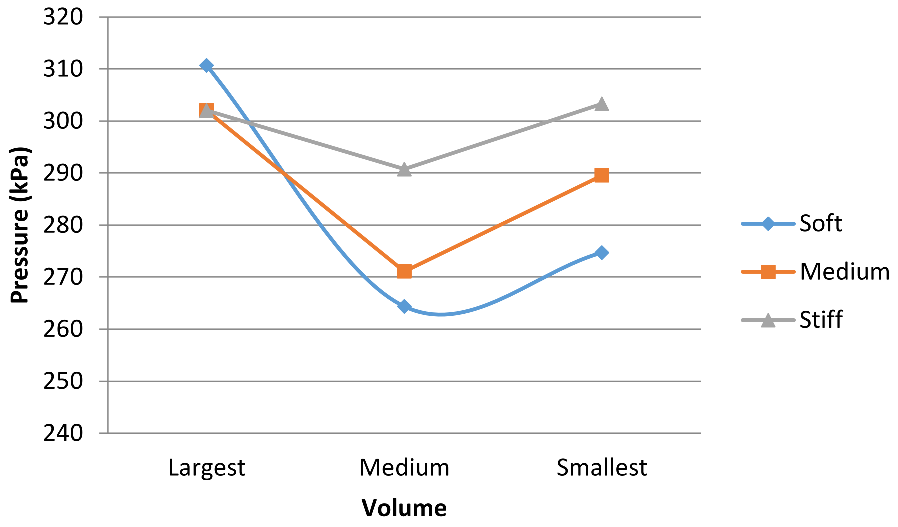

Figure 98: The interaction between Shoe Stiffness and Volume and their effect on Plantar Pressure under MT24

Heel

The heel had the lowest plantar pressure with the softest upper material and highest plantar pressures with the stiffest upper (5% increase from soft to stiff), however the effects are not statistically significant. Despite there being no change to the physical parts of the heel area there is a statistically significant increase in plantar pressure under the heel when the volume of the forefoot region is reduced (8% increase from largest to smallest volume).

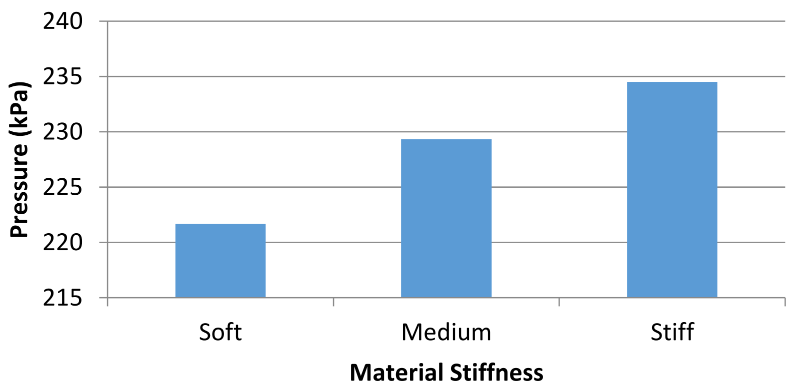

Figure 99: The effect due to material stiffness on plantar pressure in the heel region

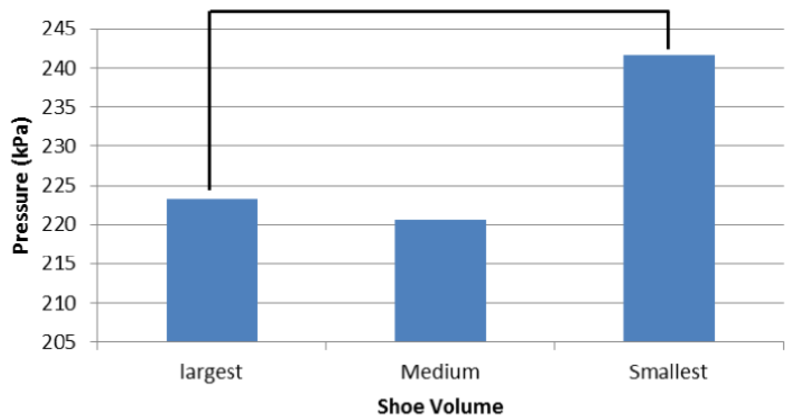

Figure 100: The effect due to shoe volume on plantar pressure in the heel region

Mauchly's test show that the data is spherical for material stiffness ($X^2(2) = 0.996$) and for the comparison of volume and stiffness ($X^2(9) = 6.578$), but not for volume ($X^2(2) = 9.429$). From the ANOVA results it is clear that there is a statistically significant effect at the heel due to volume ($F(1.483,34.110)=4.829$,$p = 0.022$) where a reduction in shoe volume increased plantar pressure under the heel. From the Benferroni pairwise comparison it is evident that there is a statistically significant difference between the smallest and largest volume shoes (p= 0.010). No other results are statistically significant.

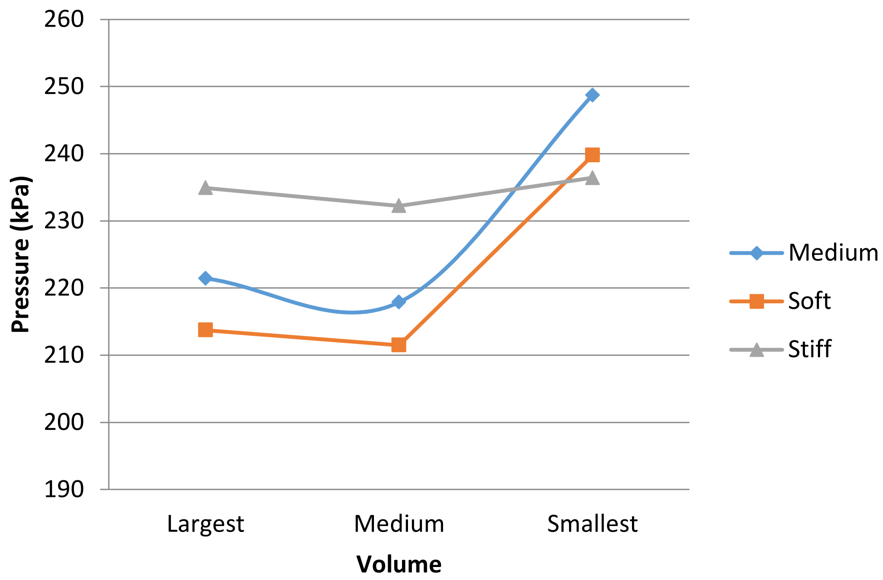

Figure 101: The interaction between Shoe Stiffness and Volume and their effect on Plantar Pressure under Heel

Hallux

There is an 8% reduction in plantar pressure from the soft upper to the stiff upper. For shoe volume there is a 7% increase in plantar pressure at the hallux from the largest to the smallest volume. However, there are no statistically significant differences between individual shoes.

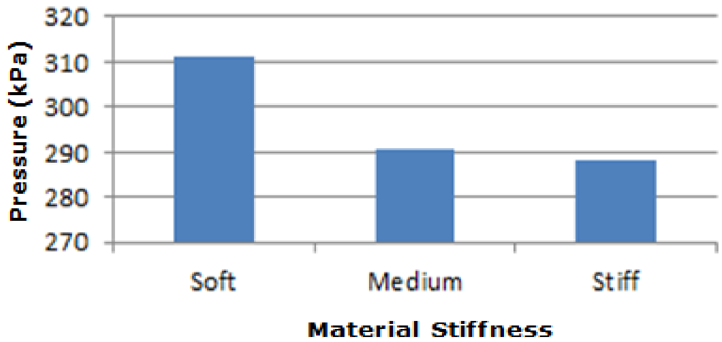

Figure 102: The effect due to material stiffness on plantar pressure in the Hallux region

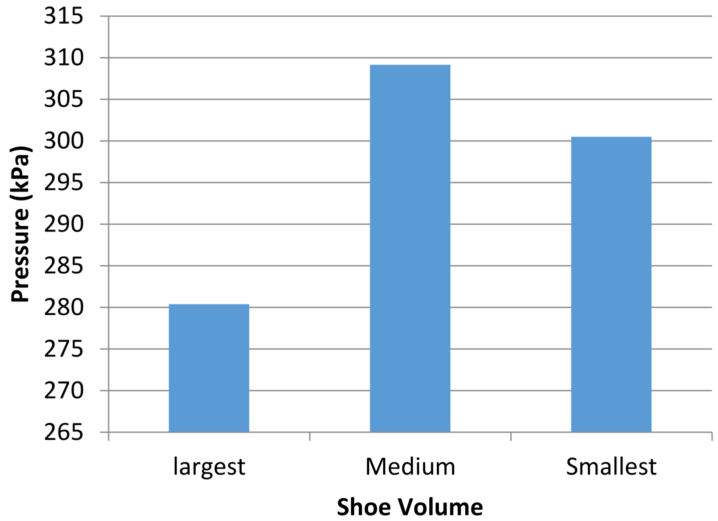

Figure 103: The effect of shoe volume on plantar pressure in the Hallux region

Mauchly's test show that the data is spherical for material stiffness ($X^2(2) = 5.034$) but not volume ($X^2(2) = 14.285$) or the comparison of material stiffness and volume ($X^2(9) = 17.444$). The ANOVA results show there is a statistically significant effect due to material stiffness ($F(2,46)=4.948$, $p=0.016$) at the hallux. The Benferroni pairwise comparison did not give any statistically significant result.

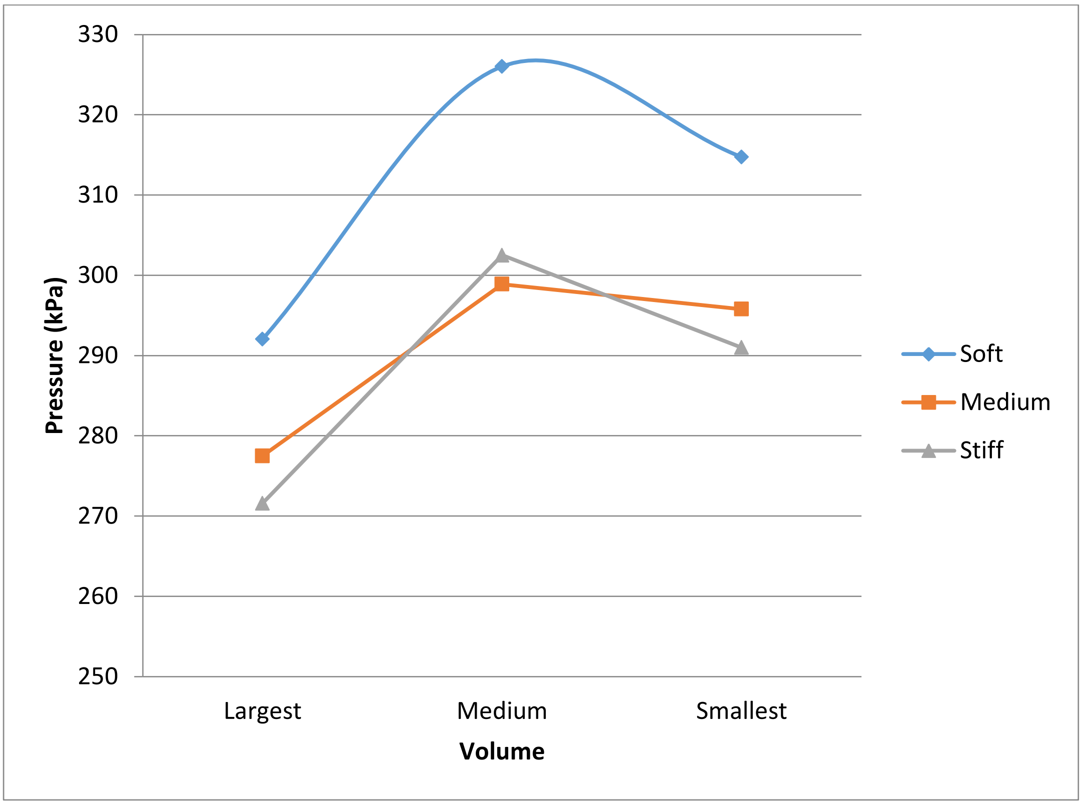

Figure 104: The interaction between Shoe Stiffness and Volume and their effect on Plantar Pressure under Hallux

Repeated measures

Of all the foot regions tested in the repeat trials (of the largest volume shoe with medium stiffness materials) there is only one statistically significant difference. This is between the first and third trial (p=0.049) and in the MT24 region. Similar to chapter 4, this result was between the first trial and either the second or third trial, never the second and third trial. As per chapter 4, data from the first trial was therefore only used for the purpose of the repeated measure test all in all other cases data from the second trial on the largest volume and medium stiffness shoe was used.

5.4.2. The effects on comfort of changing the volume of the shoe and the upper material stiffness.

It is apparent from the following results that there are statistically significant changes in comfort due to both variation of material stiffness and shoe volume. Despite the shoe volume only being changed in the forefoot area the effect on comfort was seen across all regions of the foot. Whilst in most regions of the foot there is a statistically significant difference in comfort between only the largest and smallest shoe volumes, in the toe region there was a statistically significant difference between all three volume conditions (108% increase from largest to smallest).

Overall Discomfort

The results show that for overall discomfort there are effects due to both material stiffness and shoe volume. The results show the stiffer the material the higher the score given and therefore the greater the discomfort of the shoe. There was a 48% increase in discomfort from the soft to the stiff upper shoe, although the medium and soft upper shoe scored very similarly. There was a statistically significant increase in discomfort with a reduction in volume (106% increase in discomfort from largest to smallest volume).

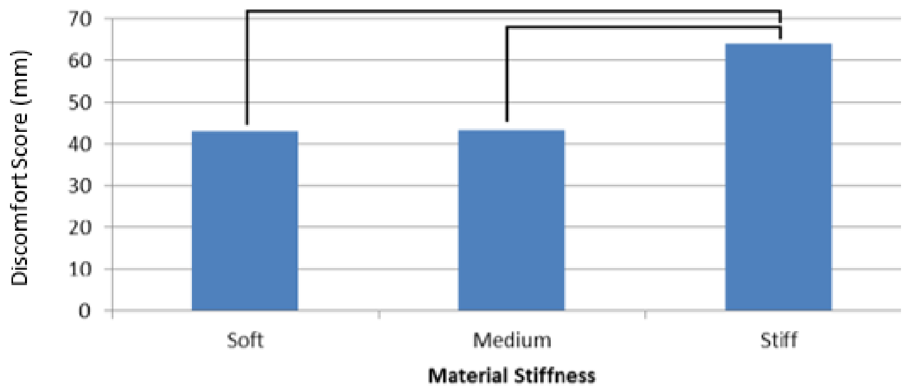

Figure 105: The effect of material stiffness on overall discomfort (higher the score the greater the discomfort)

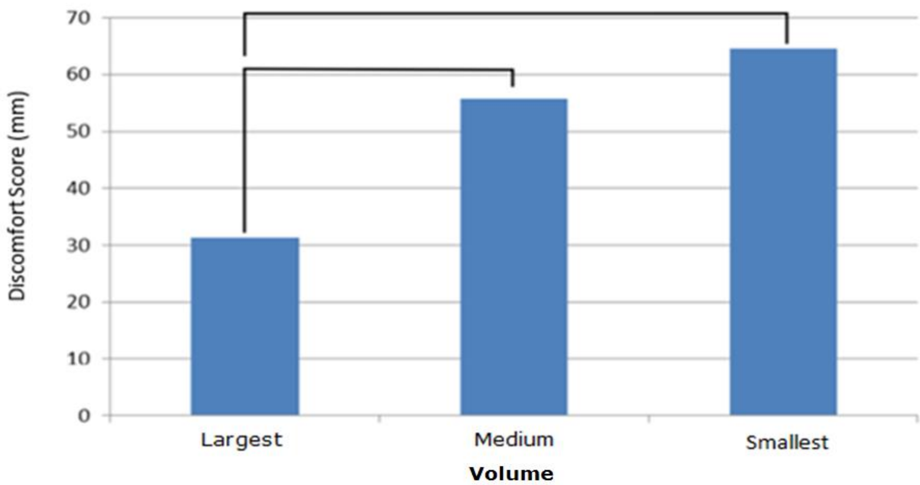

Figure 106: The effect of shoe volume on overall discomfort (higher the score the greater the discomfort)

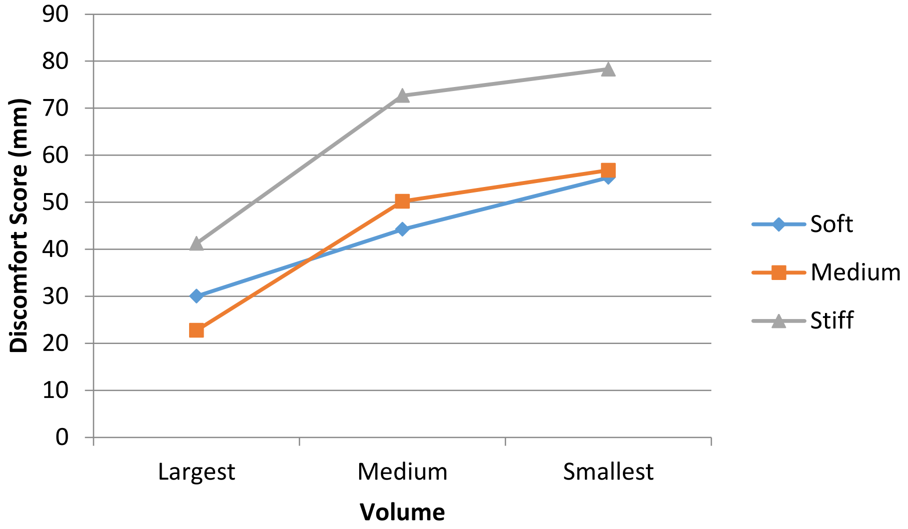

Figure 107: The interaction between upper material stiffness and shoe volume and their effect on overall discomfort (higher the score the greater the discomfort)

Mauchly's tests show that the data is not spherical for any of the three tests. The ANOVA results show that there is a statistically significant main effect due to material stiffness (F(1.825, 36.508)=11.649 p=0.000) and volume (F(1.882,37.632)=14.631 p=0.000). The Bonferroni pairwise comparison shows that there is a statistically significant difference between the softest and stiffest material (p=0.003), and the medium and stiff materials (p=0.001). There was also a statistically significant difference between the largest volume and both the medium (p=0.008) and smallest (p=0.000) Volumes.

Overall width

The overall width discomfort results are very similar to the overall comfort results, with increased material stiffness resulting in an increase in discomfort (40% reduction in comfort from the soft to the stiff upper shoe). An increase in discomfort is also observed when volume is reduced (106% increase from the largest to smallest volume).

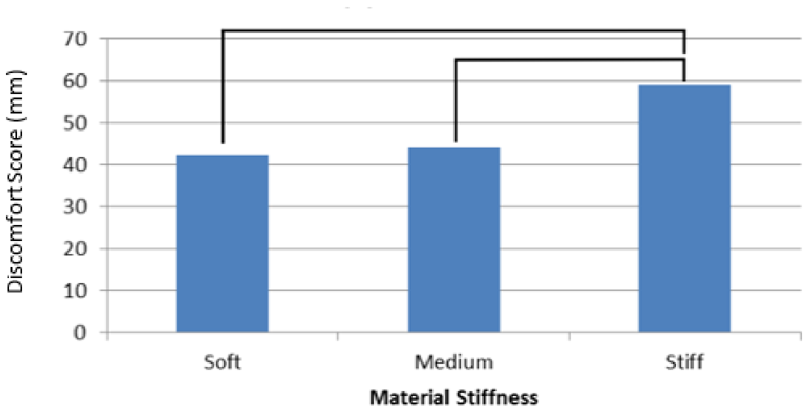

Figure 108: The effect of upper material stiffness on overall width discomfort (higher the score the greater the discomfort)

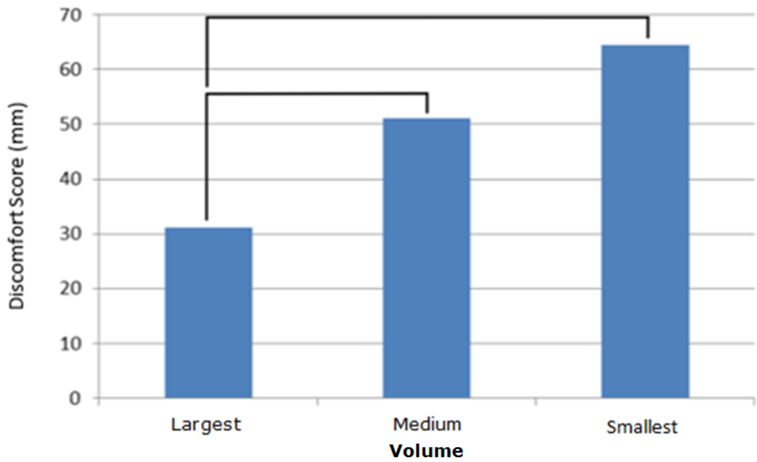

Figure 109: The effect of shoe volume on the overall width discomfort (higher the score the greater the discomfort)

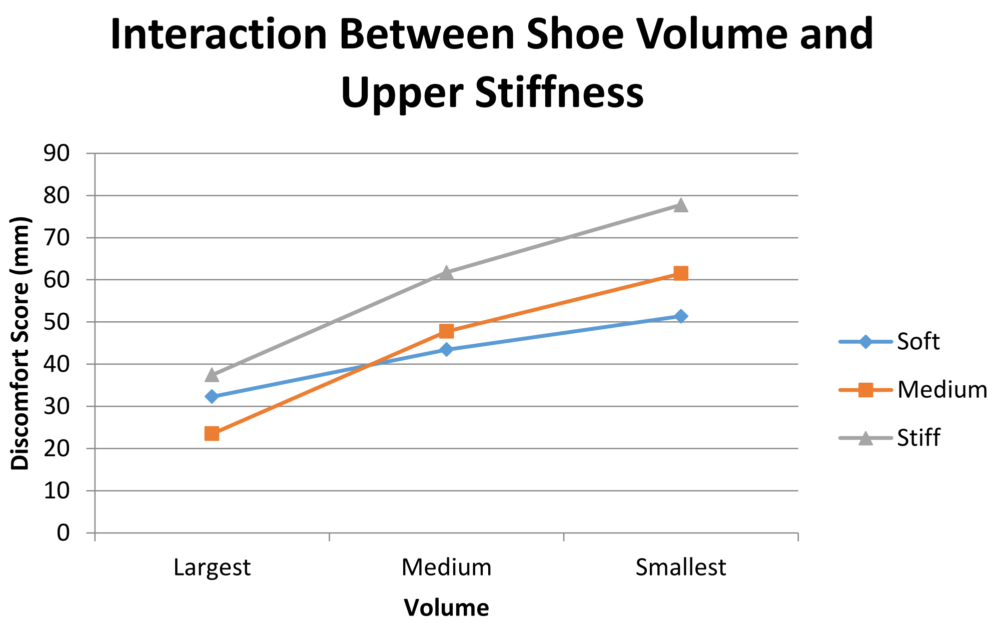

Figure 110: The interaction between upper material stiffness and shoe volume and their effect on oveall width discomfort (higher the score the greater the discomfort)

Mauchly's test shows that the data is not spherical for any of the tests. The ANOVA test reveals that there is a statistically significant main effect due to material stiffness (F(1.750, 34.999)=6.703 p=0.005), volume (F(1.910, 38.190)=14.463 p=0.000), and the interaction of material stiffness and volume (F(3.451, 69.017)=2.643 p=0.048). The Bonferroni pairwise comparisons reveal that there is a statistically significant difference between the softest and stiffest material (p=0.022), as well as the medium and stiff materials (p=0.032). For volume there is a statistically significant difference between the largest volume and both the medium (p=0.015) and the smallest (p=0.000).

Overall length

Despite all the shoes being the same length there is evidence of statistically significant effects on the reported overall length discomfort when both material stiffness and shoe volume were changed. There is little difference between the soft and medium upper shoes but there is a 37% increase in length discomfort for the stiff material compared to medium stiffness. For shoe volume there is a more linear trend, with an incremental reduction in volume producing an incremental increase in discomfort (24% increase from medium to smallest).

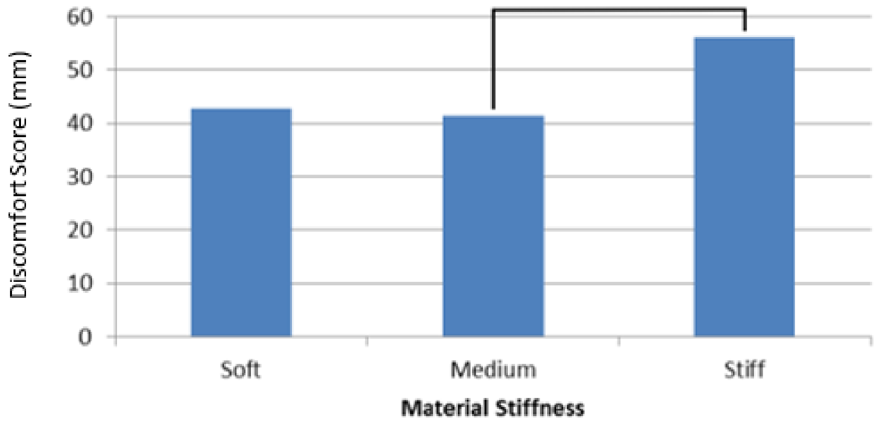

Figure 111: The effect of upper material stiffness on overall length discomfort (higher the score the greater the discomfort)

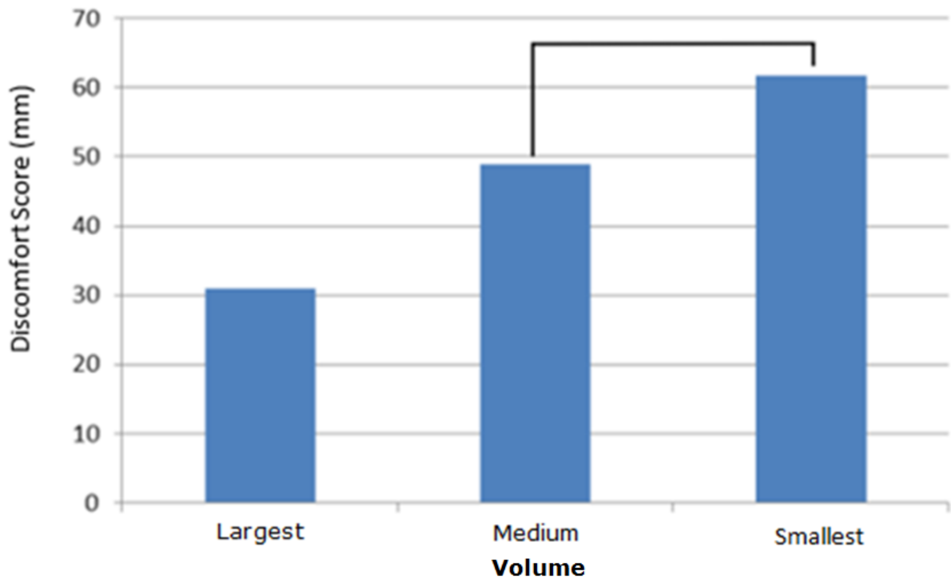

Figure 112: The effect of shoe volume on overall length discomfort (higher the score the greater the discomfort)

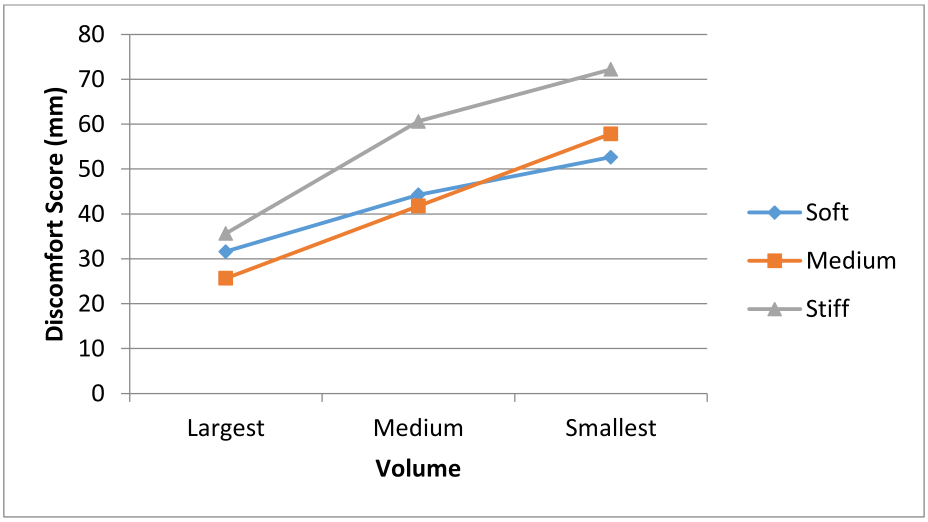

Figure 113: The interaction between upper material stiffness and shoe volume and their effects on overall length discomfort (higher the score the greater the discomfort)

Mauchly's test show that he data is spherical for the material stiffness ($X^2(2)=15.318$) only. The ANOVA tests reveal that there was a statistically significant main effect due to material stiffness ($F(2,38)=3.772$ $p=0.032$) and volume ($F(1.834,34.845)=7.786$ $p=0.002$). The Bonferroni pairwise comparisons show that there is a statistically significant difference between the medium and stiff ($p=0.025$) shoes. Whilst for volume there is a statistically significant difference between the largest and smallest volumes ($p=0.008$).

Discomfort of the sole of the foot in the heel region

The stiff material is clearly more uncomfortable than the other two materials (38% increase in discomfort from soft to stiff material) and the largest volume condition was significantly reduced discomfort than two smaller volumes (44% increase in discomfort from largest to smallest).

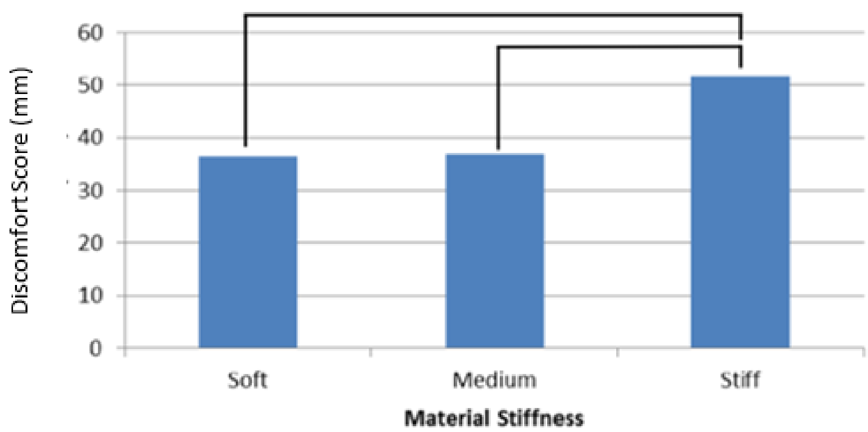

Figure 114: The effect of upper material stiffness on the discomfort of the sole of the foot in the heel region (higher the score the greater the discomfort)

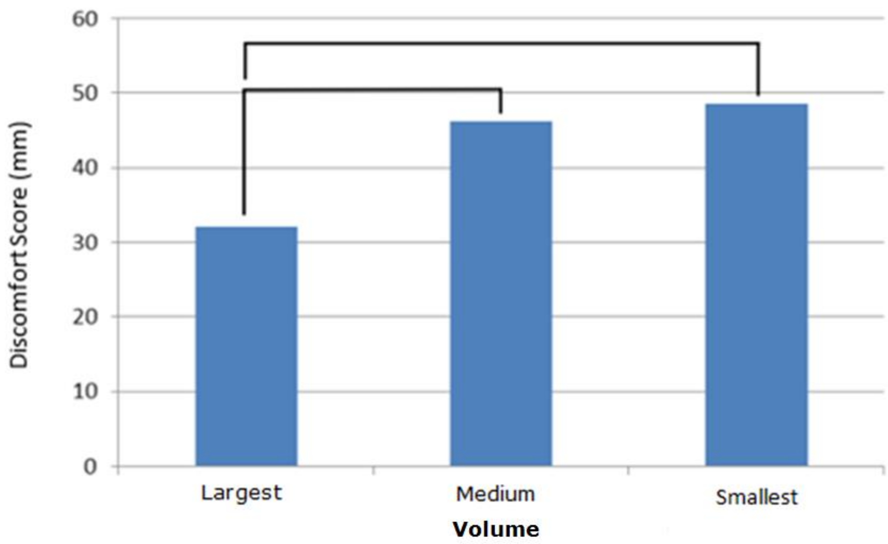

Figure 115: The effects of shoe volume on the discomfort of the sole of the sole of the foot in the heel region (higher the score the greater the discomfort)

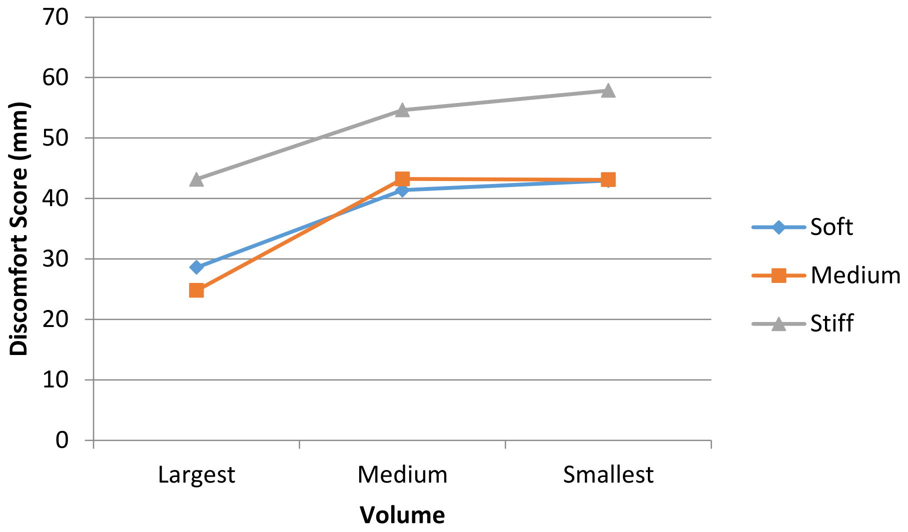

Figure 116: The interaction between shoe volume and upper stiffness and their effect on the discomfort of the sole of the foot in the heel region (higher the score the greater the discomfort)

The Mauchly's test revealed that the data is not spherical for any of the measures. The ANOVA tests show that there was a statistically significant main effect due to material stiffness ($F(1.796, 34.130)=8.546$ $p=0.001$) and volume ($F(1.900,36.103)=7.064$ $p=0.003$). The Bonferroni pairwise comparisons show that there is a statistically significant difference between the stiffest material and both the softest ($p=0.013$) and medium ($p=0.008$) material. There is also a statistically significant difference between the both the largest volume and both the medium ($p=0.037$) and smallest ($p=0.009$) volume conditions.

<u>Back of the Heel</u>

The discomfort score more than doubled between the smallest and the largest volume conditions. There was also a 48% increase in the discomfort score when the shoe was changed from the softest to the stiffest material.

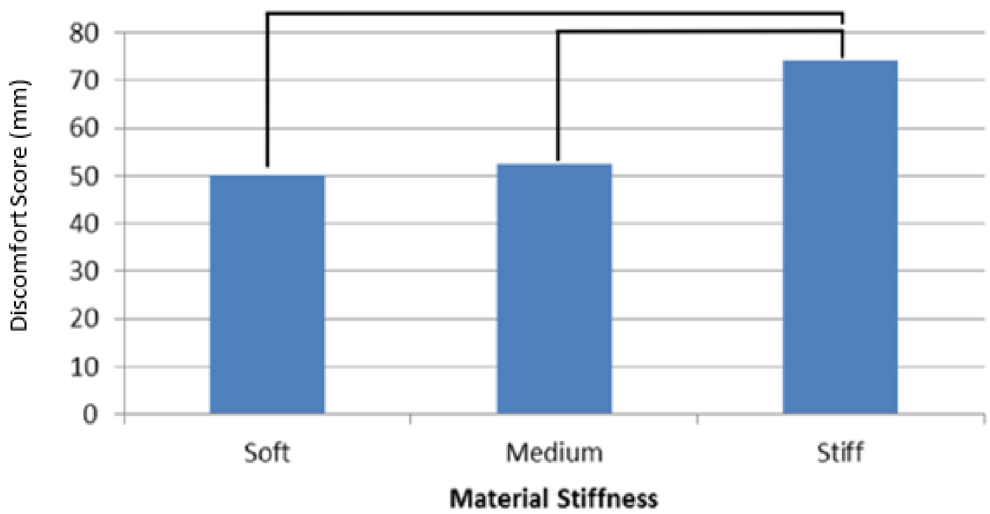

Figure 117: The effect of upper material stiffness on the discomfort of the foot at the back of the heel (higher the score the greater the discomfort)

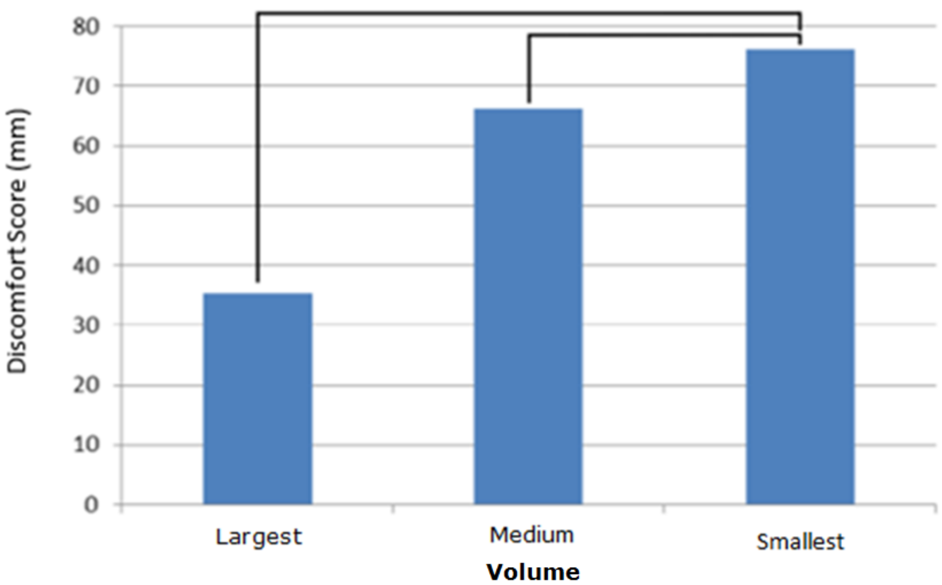

Figure 118: The effect of shoe volume on the discomfort of the foot at the back of the heel (higher the score the greater the discomfort)

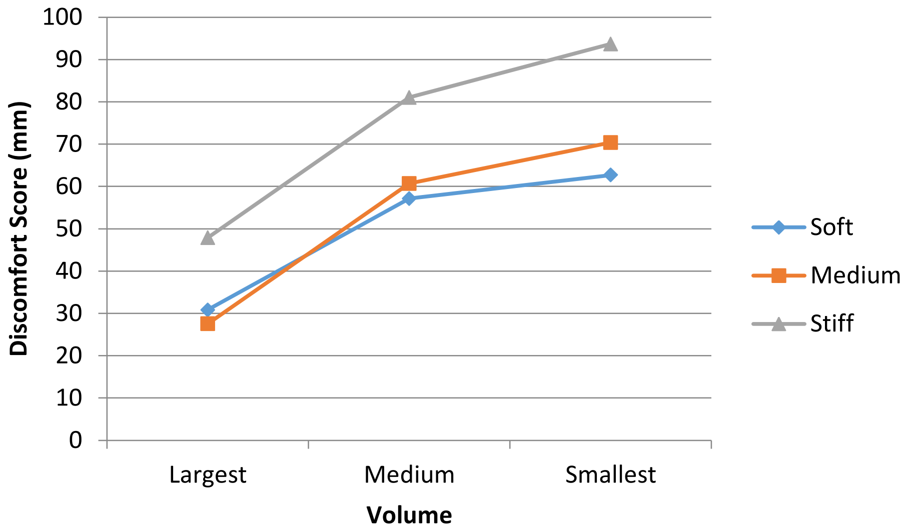

Figure 119: The interaction between shoe volume and upper stiffness on the discomfort of the foot at the back of the heel (higher the score the greater the discomfort)

Mauchly's test showed that the data is not spherical for any of the measures. The ANOVA tests revealed that there is a statistically significant main effect due to material stiffness (F(1.793,35.860)=11.175 p=0.000) and volume (F(1.906,38.124)=18.335 p=0.000). The Bonferroni pairwise comparisons show that there is a statistically significant difference between the softest and stiffest shoes (p=0.004), and the medium and stiffest shoes (p=0.001). For volume tests there is a statistically significant difference between the largest volume condition and both the medium (p=0.002) and smallest volume condition (p=0.000).

The Top of the Foot, the Dorsal Surface Discomfort

The soft and medium stiffness shoes show very similar results whereas there is a statistically significant increase in discomfort reported for the stiff upper shoes compared to both the medium and soft upper shoes (47% increase from soft to stiff material). For shoe volume there is a more linear effect where a reduction in volume increases discomfort (80% reduction from smallest to largest volume). From the interaction plot it is clear that all three materials have similar effects due to change in volume. Whilst the soft and medium upper shoes report similar results for each of the three volume conditions, the stiff upper shoes are less comfortable for all volumes.

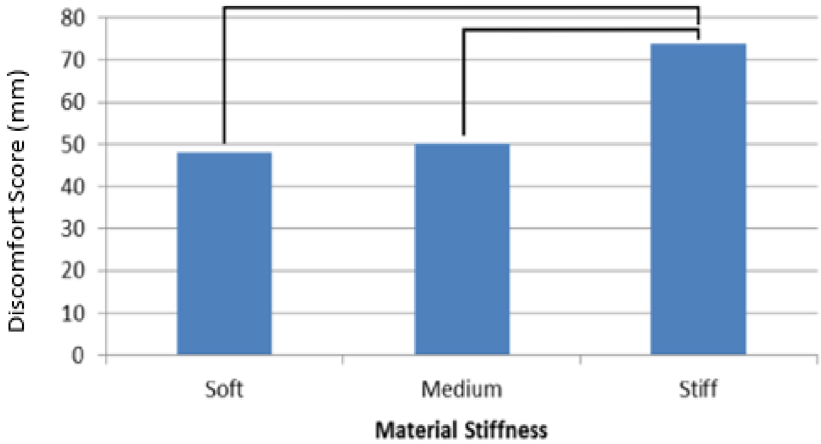

Figure 120: The effect of upper material stiffness on the discomfort on the dorsal surface of the foot (higher the score the greater the discomfort).

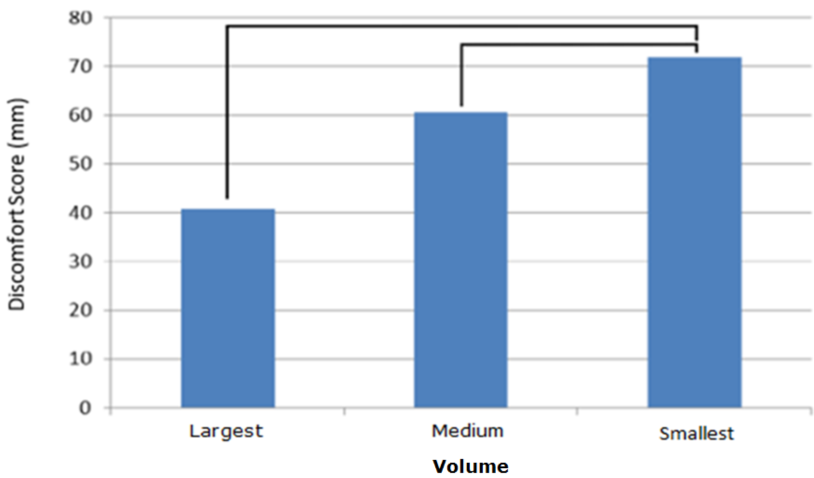

Figure 121: The effect of shoe volume on the discomfort of the dorsal surface of the foot (higher the score the greater the discomfort).

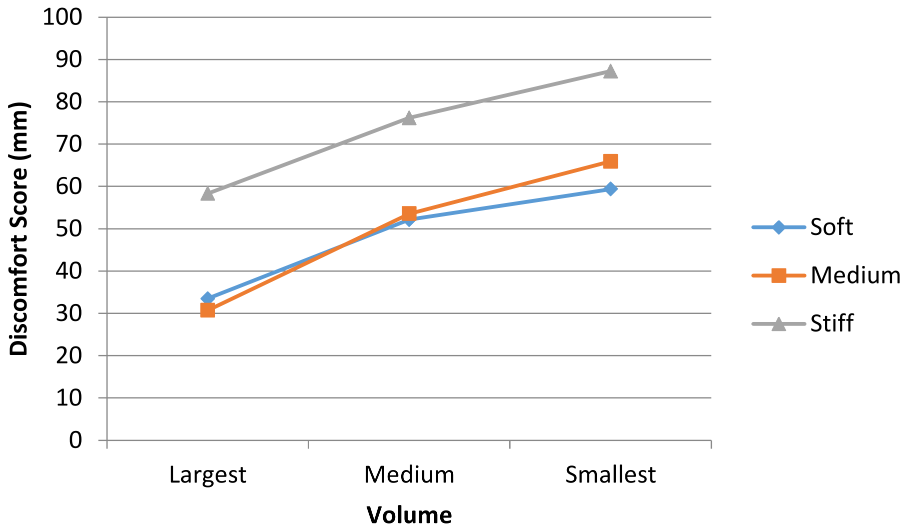

Figure 122: The interaction between shoe volume and upper stiffness and their effect on the discomfort of thee dorsal surface of the foot (higher the score the greater the discomfort)

Mauchly's test show that the data is spherical for material stiffness ($X^2(2)=7.209$) and the interaction of material stiffness and shoe volume ($X^2(9)=21.011$). The ANOVA results show that there is a statistically significant main effect due to material stiffness ($F(2,38)=10.855$ $p=0.000$) and volume ($F(1.802,34.230)=13.109$ $p=0.000$). The Bonferroni pairwise comparisons reveal that there is a statistically significant difference between the stiffest and both the softest ($p=0.007$) and medium ($p=0.004$) materials. There is also a statistically significant difference between the smallest volume condition and both the largest volume ($p=0.000$) and medium volume ($p=0.026$) conditions.

Under the Medial Arch discomfort

The results for the medial arch are consistent with those previously observed. The stiff upper shoes are significantly less comfortable than the medium and the soft upper shoes (39% reduction from the stiff to the medium upper). The reduction in volume produces an increase in medial arch discomfort (63% reduction from largest to smallest volumes). The largest volume was significantly different to the other volume conditions for the medial arch only. However, the interactions show that the medium and stiff upper shoes follow the same trend. The soft upper when paired with the medium volume shoe is least comfortable.

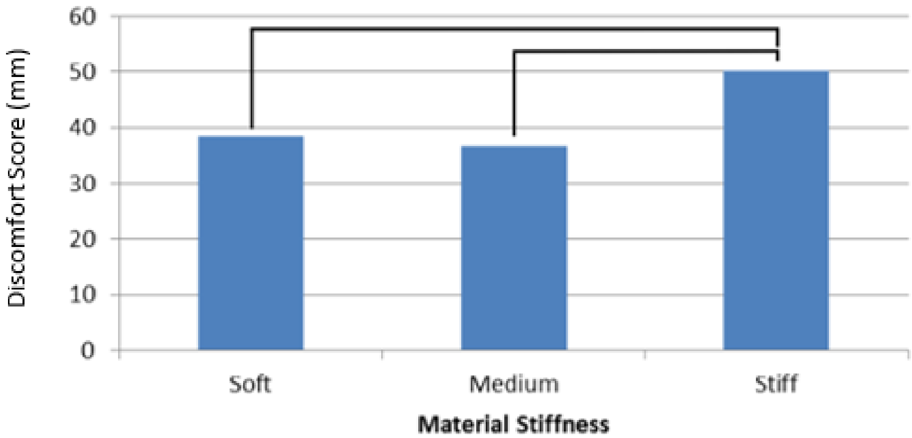

Figure 123: The effect of upper material stiffness of the discomfort experienced under the medial arch (higher the score the greater the discomfort)

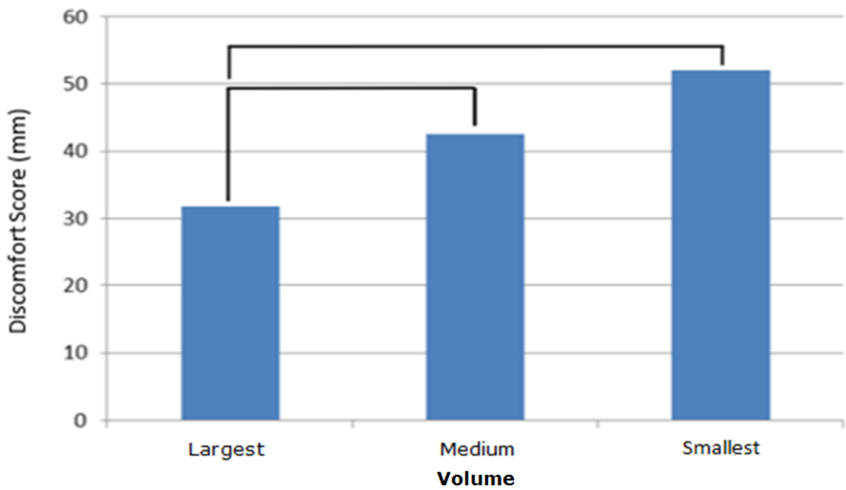

Figure 124: The effect of shoe volume on the discomfort experienced under the medial arch (higher the score the greater the discomfort)

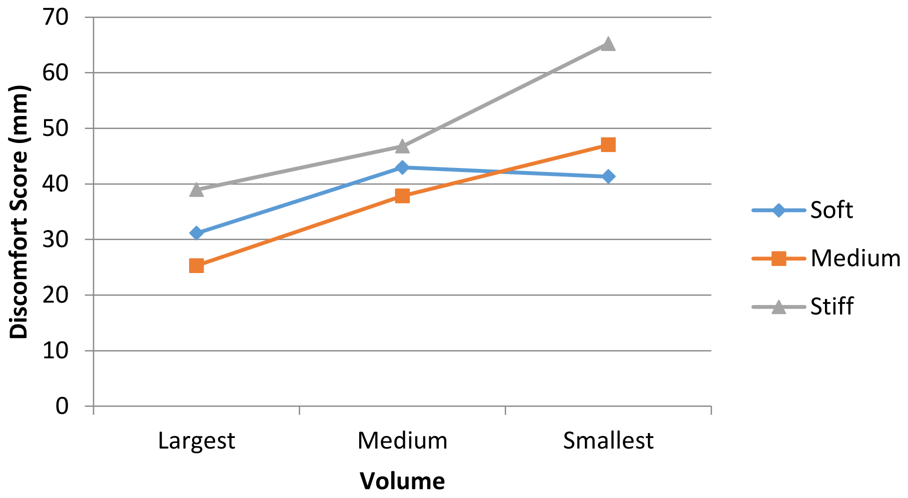

Figure 125: The interaction between shoe volume and upper material stiffness and their effect on the discomfort experienced under the medial arch (higher the score the greater the discomfort)

Mauchly's test show that the data is spherical for the interaction between shoe volume and upper material stiffness ($X^2(9)=35.241$). The ANOVA test revealed that there is a statistically significant main effect due to material stiffness ($F(1.810,36.195)=6.539$ $p=0.005$) and shoe volume ($F(1.636,32.717)=8.684$ $p=0.002$). The Bonferroni pair wise comparisons show that there is a statistically significant difference between the stiffest material and both the softest ($p=0.038$) and medium (0.0003) stiffness materials. There is also a statistically significant difference between the largest volume condition and both the medium ($p=0.046$) and smallest ($p=0.004$) volume conditions.

The Sides of the Ball of the Foot/ the sides of the metatarsal heads discomfort

The material stiffness has a clear effect on comfort (55% increased discomfort from the soft to the stiff upper shoe), however there is little change in comfort between the soft and medium upper shoe (5% increase in discomfort from the soft to the medium stiffness upper shoe). Whilst there is a general trend that a reduction in shoe volume reduces comfort there was only a statistically significant difference between the smallest volume and the two remaining volume conditions (79% increase discomfort from the largest to smallest volumes). From the interactions it can be seen that the soft and medium upper shoe had very similar values for all shoe volumes.

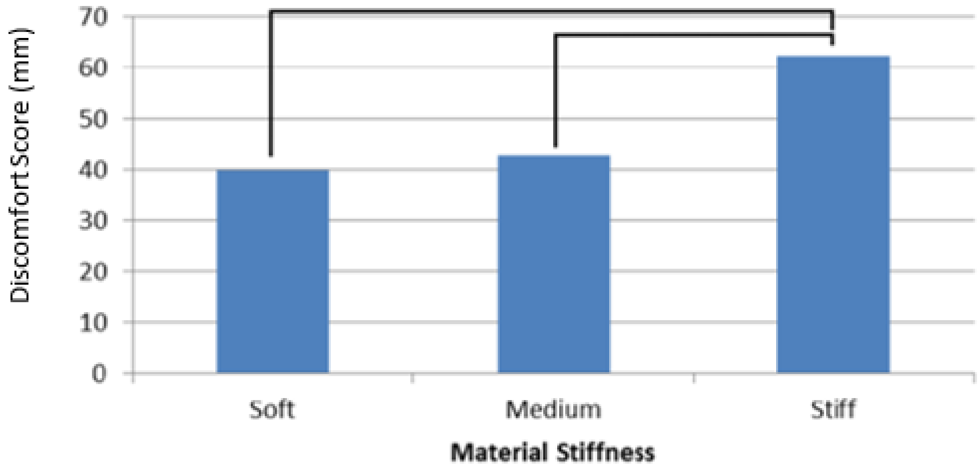

Figure 126: The effect of upper material stiffness on the discomfort experienced at the sides of the metatarsal heads (higher the score the greater the discomfort)

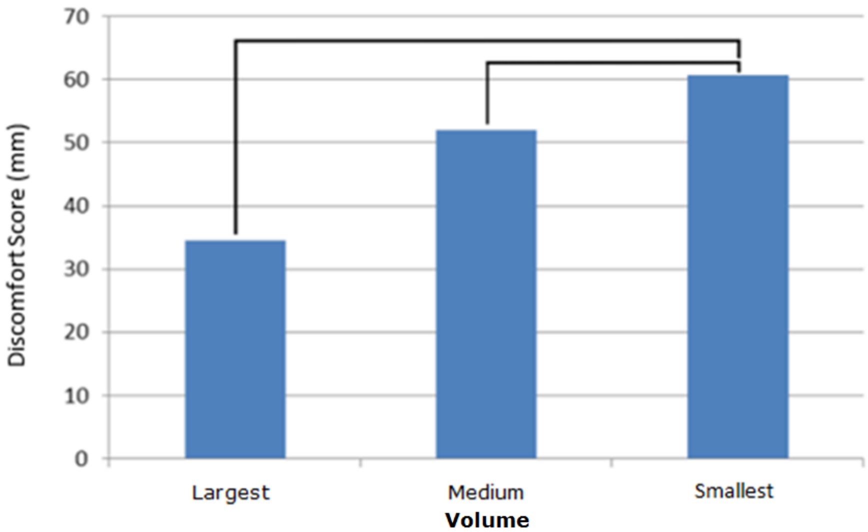

Figure 127: the effect of shoe volume on the discomfort experienced at the sides of the metatarsal heads (higher the score the greater the discomfort)

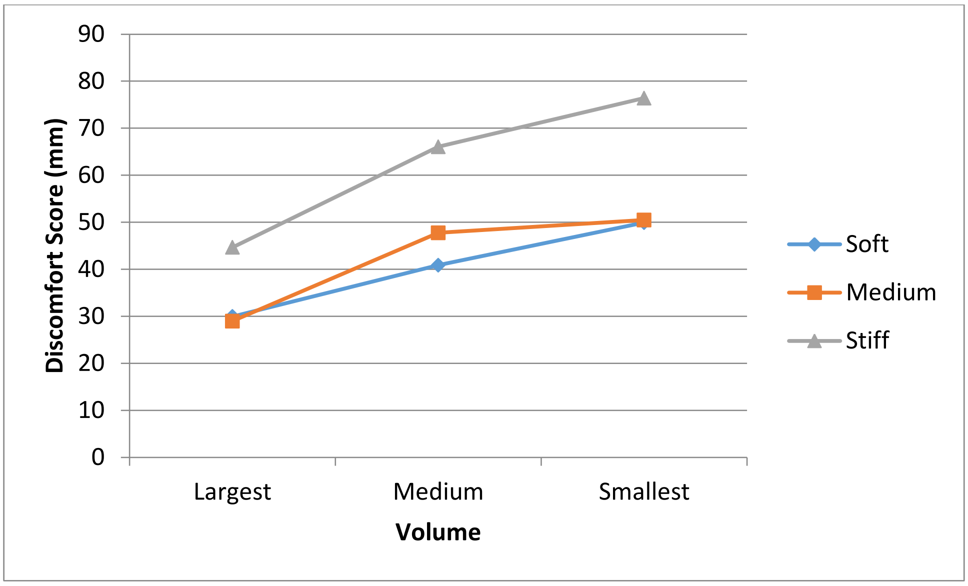

Figure 128: The interaction between the shoe volume and upper material stiffness and their effect on the discomfort experienced at the sides of the metatarsal heads (higher the score the greater the discomfort)

Mauchly's test revealed that the data is spherical for both material stiffness ($X^2(2)=14.245$) and the interaction between material stiffness and the shoe volume ($X^2(9)=42.055$). The ANOVA test show that there is a statistically significant main effect due to material stiffness ($F(2,36)=8.008$ $p=0.001$) and shoe volume ($F(1.710,30.788)=10.889$ $p=0.000$). The Bonferroni pair wise comparisons show that there is a statistically significant difference between the stiffest material and both the soft ($p=0.025$ and medium $p=0.027$) material.

Discomfort of the sole of the foot in the Ball region (under the metatarsal heads)

The only statistically significant effect was that discomfort score increased by 44% between the stiff to the medium material. There was a linear increase in discomfort when shoe volume increased (76% increase in discomfort from the largest to smallest volumes).

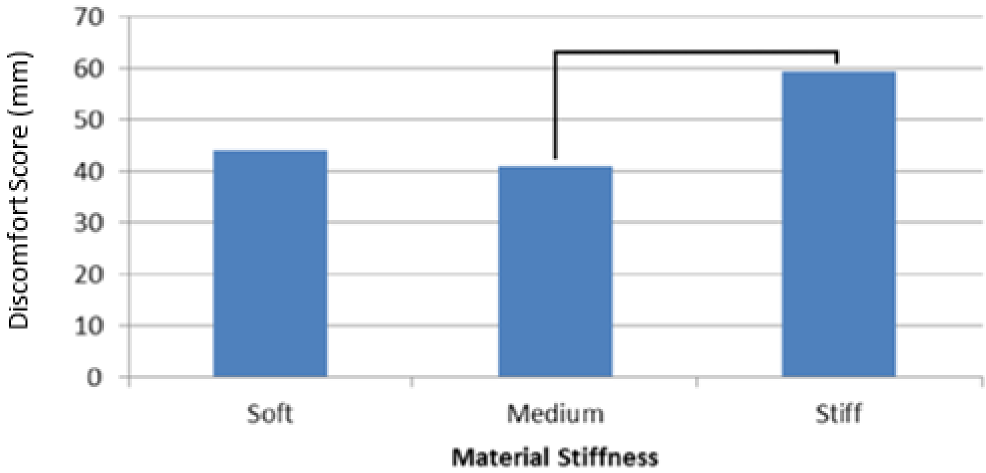

Figure 129: The effect of upper material stiffness on thedis comfort experienced on the sole of the foot in the region under the metatarsal heads (higher the score the greater the discomfort)

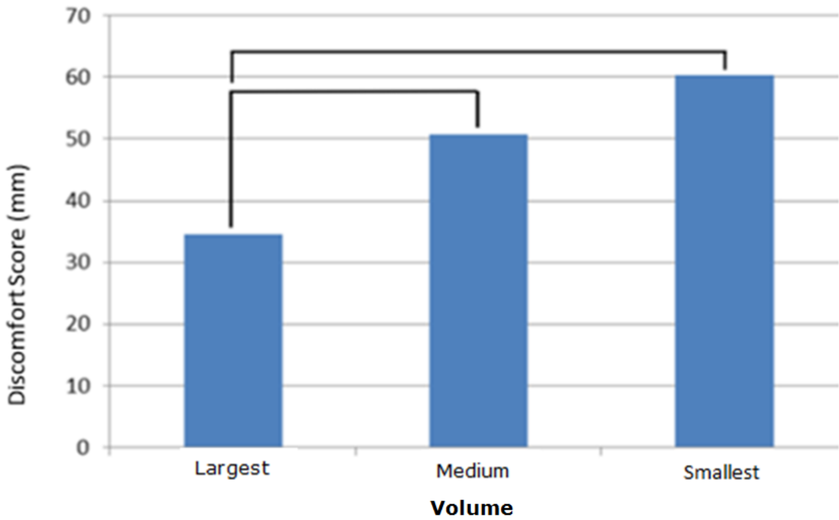

Figure 130: The effect of shoe volume on the discomfort experienced by the sole of the foot in the region under the metatarsal heads (higher the score the greater the discomfort)

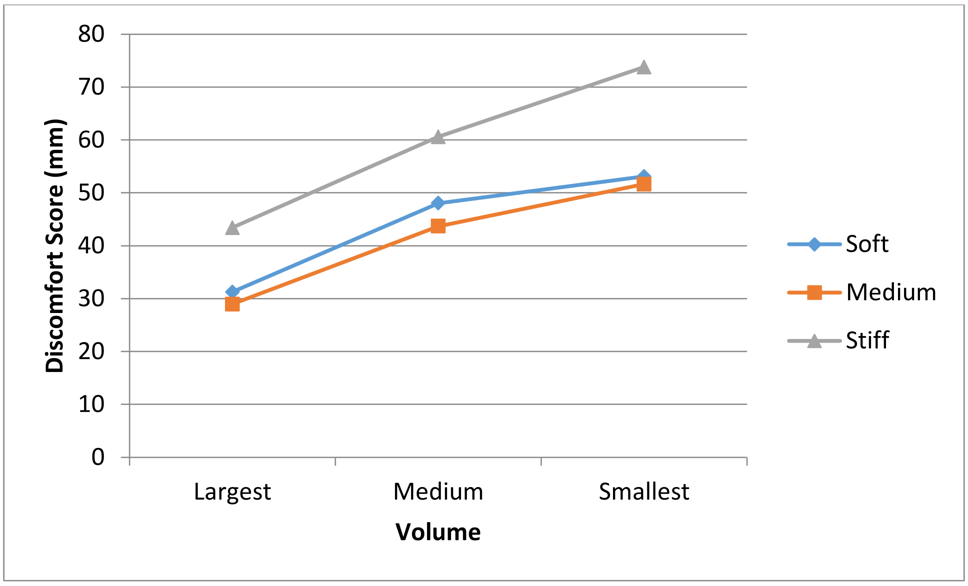

Figure 131: The interaction between shoe volume and upper material stiffness and their effect on discomfort experienced by the sole of the foot in the region under the metatarsal heads (higher the score the greater the discomfort)

Mauchly's test showed that the data is not spherical for any of the measures. The ANOVA test revealed that there was a statistically significant main effect due to material stiffness ($F(1.620,30.789)=6.414$ $p=0.007$) and shoe volume ($F(1.926,36.589)=12.284$ $p=0.000$). The Bonferroni pairwise comparison showed that there was a statistically significant difference between the medium and stiffest material ($p=0.005$). For shoe volume there was a statistically significant increase in discomfort between the largest volume condition and both the medium ($p=0.013$) and smallest volume ($p=0.001$) conditions.

Toe region discomfort

The toe region was the only region that showed no statistically significant results due to a change in material stiffness. In contrast there is a statistically significant difference between all three volumes conditions. The largest difference was between the largest and smallest volume which had a 108% increase in discomfort.

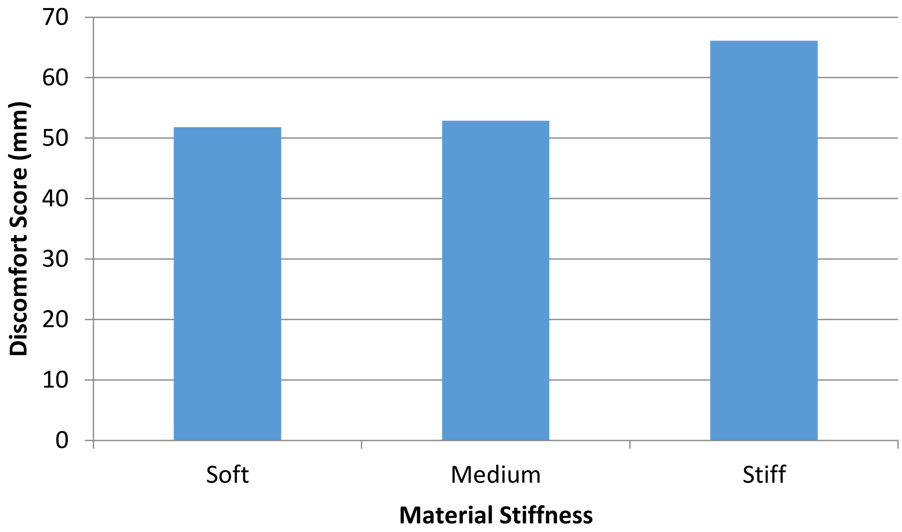

Figure 132: The effect of upper material stiffness on the discomfort experienced in the toe region (higher the score the greater the discomfort)

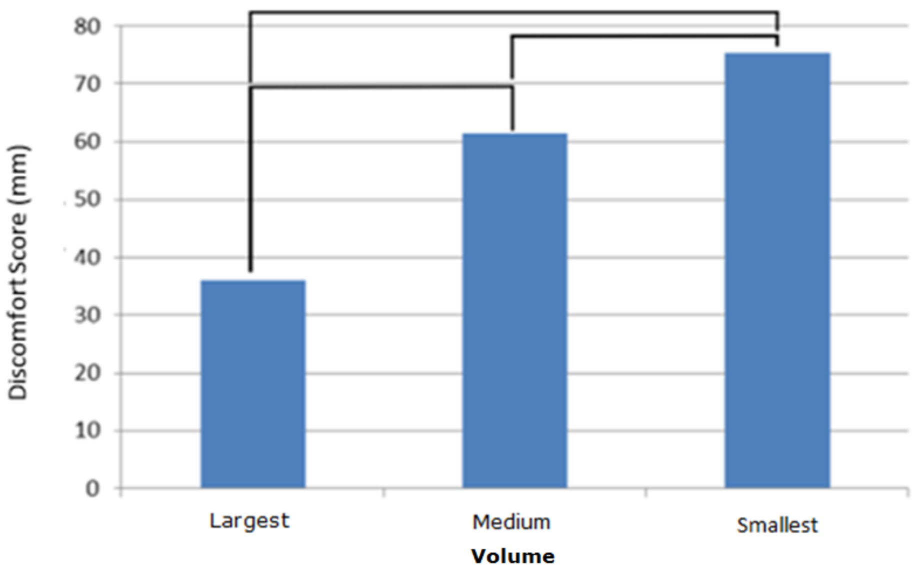

Figure 133: The effect of shoe volume on the discomfort experienced in the toe region (higher the score the greater the discomfort)

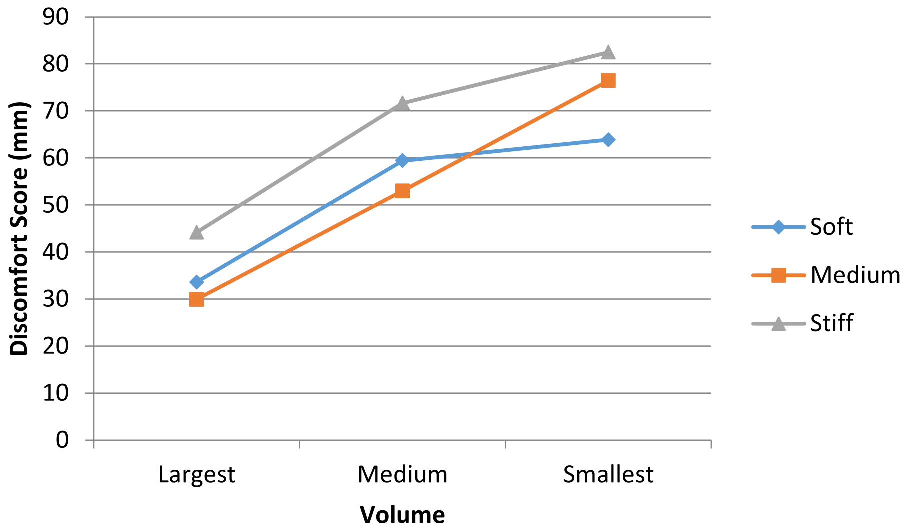

Figure 134: The interaction between shoe volume and upper material stiffness and their effect on the discomfort experienced in the toe region (higher the score the greater the discomfort)

Mauchly's test show that the data is spherical for material stiffness ($X^2(2)=10.883$) and shoe volume ($X^2(2)=7.036$). The ANOVA test revealed that there is a statistically significant main effect due to material stiffness ($F(2,38)=3.346$ $p=0.046$) and shoe volume ($F(2,38)=11.502$ $p=0.000$). The Bonferroni pairwise comparison showed there are no statistically significant difference between materials, there was however, differences for shoe volume. The largest volume condition was significantly different from the medium volume ($p=0.027$) and smallest volume ($p=0.003$) condition. There was also a statistically significant difference between the largest volume and smallest volume ($p=0.049$) conditions.

Repeated measures

For all of the comparisons made between the three repeat trials of the medium stiffness largest volume shoe, for all of the questions asked, none showed a statistically significant difference.

5.4.3. The interaction between shoe fit and comfort

During foot shape data collection the 3D scans were viewed on screen to check for large amounts of ghost points or gaps in the scans. However, errors due to loss of calibration affected several foot scan data sets and data for these was lost (11 data sets were accepted).

Two lasts were used in this study their measurements can be seen in Table 15.

Table 15: The measurements from the lasts

	Standard ball 65%		
Last size	Ball angle	Girth	Inclination angle
5	12	226.3	30
6	12	230	25

The measurements of the accepted scans of the participants' feet can be seen in Table 16

Table 16: The measurements taken from the scans of the participants' feet.

Participant number	Shoe size	Standard ball 65%		
		Ball angle note	Girth	Inclination angle
1	6	12	210.7	21.4
2	5	12	216.5	21.4
3	5	12	196.6	21.4
4	5	12	216.8	21.4
5	5	12	202.4	21.4
6	6	12	212.3	21.4
7	6	12	212.7	21.4
8	6	12	199.3	21.4
9	6	12	196.4	21.4
10	5	12	208.9	21.4
11	5	12	205.2	21.4

The difference between the foot and the last circumference is shown in Table 17.

Table 17: The difference between the foot and the last circumference of each of the participants

participants	Difference in girth between the foot and the lasts (mm)
11 right flat	19.3
12 right flat	9.8
13 right flat	29.7
14 right flat	9.5
15 right flat	23.9
16 right flat	17.7
17 right flat	17.3
18 right flat	30.7
19 right flat	33.6
20 right flat	17.4
21 right flat	21.1

The statistically significant results of the Pearson's correlation, relating the difference in last and foot circumferences for each material stiffness and shoe volume, are presented in Figure 135, and Figure 136. Due to the large number of tests (60) only the statistically significant results are shown. The primary outcome is, with increased shoe volume relative to foot size there was a reduction in the discomfort score.

Table 18: The statistically significant results from the Pearson's correlation tests on shoe volume or material stiffness vs the difference in last and foot circumference.

Question asked	Volume	Material stiffness	Pearson correlation	Significance
comfort at the back of the heel	smallest	Soft	-0.828	0.006
	Medium	Soft	-0.833	0.005

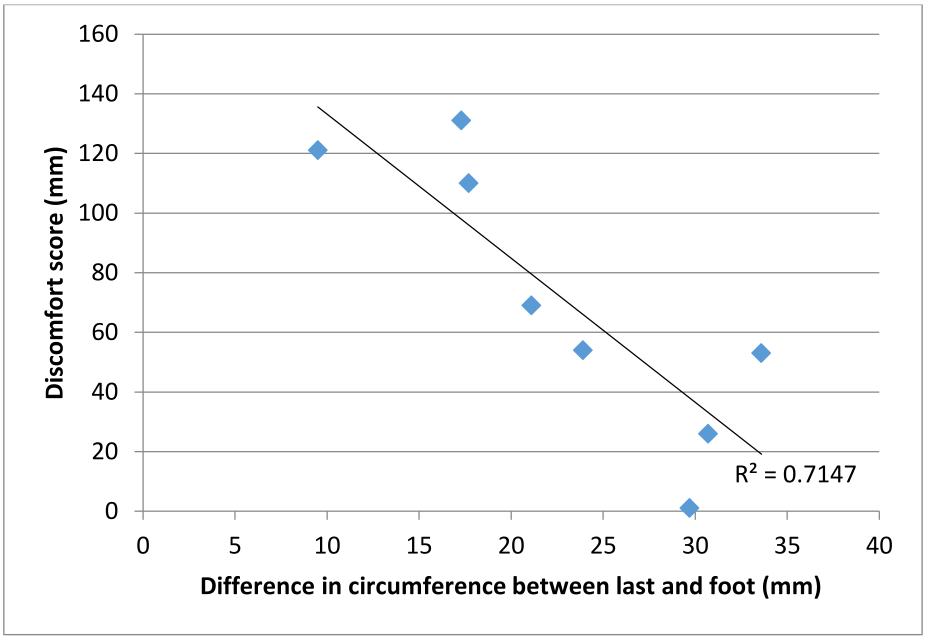

Figure 135: A comparison between the shoe/ foot circumference mismatch and the discomfort score attained for the discomfort at the back of the heel question, whist wearing the smallest volume shoe with the soft stiffness upper material. A higher comfort score signifies increased discomfort

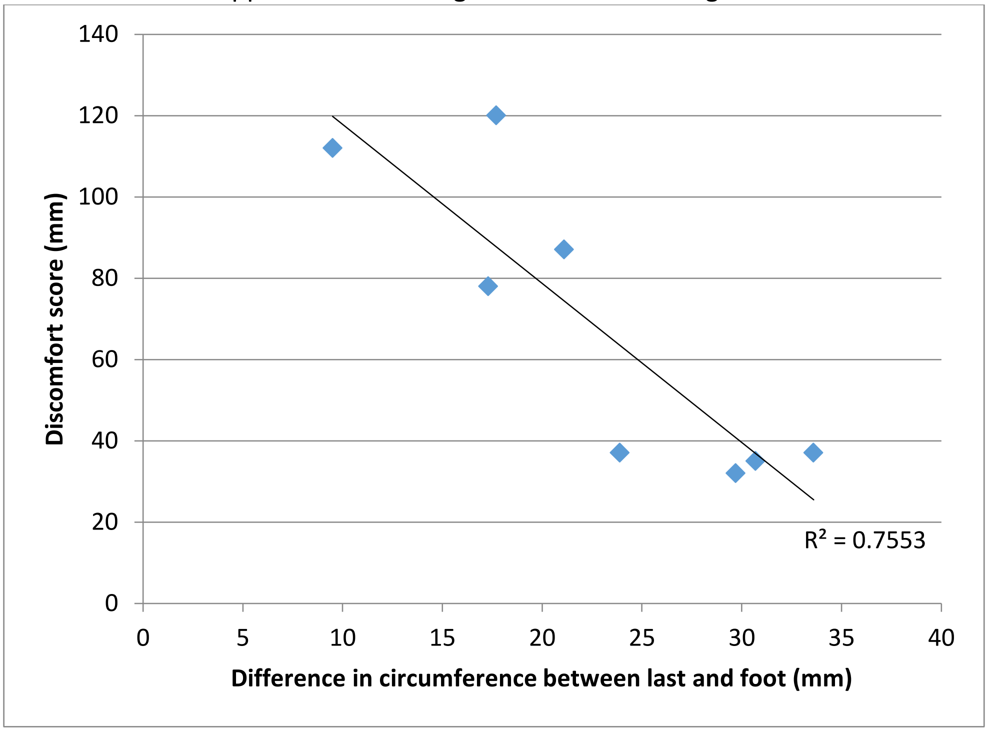

Figure 136: A comparison between the shoe/ foot circumference mismatch and the discomfort score attained for the comfort at the back of the heel question, whist wearing the medium volume shoe with the soft stiffness upper material. A higher comfort score signifies increased discomfort

5.7. Discussion

5.7.1. Introduction

This study had four primary aims, which were to identify:

1. The effects of reduced shoe volume on (A) plantar pressure and (B) comfort
2. The effects of increased material stiffness on (A) plantar pressure and (B) comfort
3. The effects of interaction between shoe volume and material stiffness on (A) plantar pressure and (B) comfort
4. If a correlation between fit and comfort exists.

To enable ease of discussion the effects of shoe volume and material stiffness will be reviewed together with regards to their effect on plantar pressure and then separately their effects on comfort.

<u>The effects of changing forefoot shoe volume and material stiffness on plantar pressure</u>

An increase in shoe volume increased the plantar pressure at the MTP1 and reduced it at the heel, which is the opposite of the first hypothesis in this study. For the MTP1 the medium and small volume shoes show very similar plantar pressures (257.2 and 250.2kPa respectively) which were both significantly lower than plantar pressures in the largest volume shoe (281.4kPa). The medium volume shoe produced the lowest plantar pressure at the MT24. This proved the second hypothesis wrong, which had predicted a linear change in pressure as volume was systematically decreased. At the heel the plantar pressure reduced when the volume was increased, and there was also a difference between the largest volume shoe and the other two smaller volumes, a similar but opposite effect was seen at the MTP1 where increased volume increased pressure. This supports the theory that increased volume causes the plantar pressure to move from the heel to the MTP1, an effect previously reported [79]. The change occurred between medium and largest volume shoes rather than a gradual change as volume was incrementally increased. This could be indicative of a ‘threshold’ for the effect of shoe volume. For example, when volume is reduced to a specific state (perhaps close to the medium volume in this study) further reductions in volume may have no further effects on plantar pressure in the forefoot, nor in the heel.

There is a difference in the effect of shoe volume on the MTP1 and MT24, whilst the MTP1 has a linear increase in pressure the MT24 experiences its lowest pressure for the medium volume shoe. Past studies have suggested that footwear features that will reduce the volume such as narrow and shallow toe boxes would increase the pressure at the forefoot [10, 114] however the results from the current study show that there is a more complex relationship. Past studies have also suggested that tight fitting uppers can lead to foot health conditions such as Morton’s neuroma and metatarsalgia [114, 240]. For conditions such as these to persist there needs to be an increase in pressure in the intermetatarsal space. It is possible that the pressure in the intermetatarsal space is increased via the engagement of a transverse arch across the forefoot. Such an arch would explain the increase in pressure at the MTP1 with a corresponding reduction in pressure at the MT24, as the inherent shape of the arch would offload the MT24 and load the MTP1. The results of this study may in fact be showing us that there is an optimum forefoot volume for which a transverse arch occurs, however, without further investigation this cannot be confirmed. If such an optimum volume does exist then this would be an important finding to footwear manufactures and foot health professionals as the avoidance of this volume could be essential for foot health.

The relationship between the pressure at the forefoot and the heel is perhaps easier to explain than other regions. Since the loading required for ambulation is a constant for an individual walking at constant speed, an increase in pressure in one region will result in a reduction in another. Since the pressure is increased in the medial forefoot, the pressure in the rear of the foot i.e. the heel is reduced. Whilst this is not conclusive from the current results, because not all the data from all the regions was available, the findings of this study are in agreement with many past papers. These also show that with an increase in pressure at the forefoot the pressure at the heel is reduced. The results of studies showing this effect can be seen in Table 2, in chapter 3.

The material's stiffness tests showed that an increase in material stiffness reduces plantar pressure at the MTP1 (soft 268.8kPa, stiff 256.64kPa) and increases it at the MT24 (soft 283.2kPa, stiff 298.7kPa). This shows the opposite of that predicted in hypothesis four, and shows that the results in this study are the opposite of that seen in the previous chapter. There was also a statistically significant main effect which showed that the plantar pressure increased at the hallux when the material stiffness increases. The reasons for these effects are not clear since they are different to both the volume data in this chapter and the material stiffness data in the previous chapter. Since, material stiffness showed statistically significant results in both chapters, it is clear that changing the upper can have an effect. However, how this happens and what is causing the effect is not clear from these investigations. One such possibility is that the materials tested do not have the characteristics that were expected.

To investigate this further the materials were sent to INESCOP, Spain so that materials testing could be conducted on them. Unfortunately, due to the destructive nature of the tests they had to be conducted after all other investigations had been carried out. The tests conducted by INESCOP included: Determination of leather stiffness (ISO 5403-1:2011, clause 6.1), Determination of softness (ISO 17235:2011), and Tensile strength (ISO 3376:2011) and shows the results.

Shoe	Bovine Suede (soft)		Goat Leather (medium)		Bovine Leather (stiff)	
Foot	right	left	right	left	right	left
Test Conducted						
Leather Stiffness						
2mm compression	1.7	2	0.8	0.9	6.6	7.2
4mm compression	2	2.2	0.8	0.9	6.4	7.2
6mm compression	2.2	2.3	0.8	0.9	6.5	7.4
mean	2.07		0.85		6.88	
Softness * (mm	6.4	7	7	6.4	4.6	4.3
distension)	6	7	7	6.9	4.5	4.3
	6.5	6.5	7	7.1	4.5	4.1
mean	6.56		6.9		4.38	
Tensile Strength (N/mm^2)	25.4	19.8	24.5	26.5	18.5	19.5
Elongation at break (%)	57	49	47	47	51	39
Thickness	1.47	1.53	0.65	0.64	1.41	1.5

Figure 137: The results of the material tests conducted by INESCOP, Spain.

The results highlight that despite only asking for one characteristic to change between the materials several aspects of the materials differed. This is because it is very difficult, particularly when animal hides are used, to keep material characteristics constant. Since leather is made from animal hides it is subject to the natural differences between each individual animal it is taken from. Furthermore, the hide will vary for the different regions of the animal, in both the thickness and the stiffness. The final leather product also has a grain, which are the remnants of the graining on the skin of the animal. This graining does not have universal characteristics and as a result the leathers stiffness properties will be different dependent upon the direction in which the material is put under strain.

INESCOP was asked to complete the tests they would normally be asked to conduct on shoes by the footwear industry. It was apparent from these results that the tests completed were focused on manufacturing standards. It was assumed that the use of manufacturing standards was the reason that, despite completing a tensile strength test, only the load required to break the material and its elongation at break were measured. To do this the materials are tested to destruction despite this being unlikely during the product's normal operational life. This sort of test might therefore be insensitive to differences in materials that are well within its normal operational range.

The modulus of elasticity or young's modulus is a measure of stiffness. It is the linear section of the stress strain curve also known as the elastic region. The modulus of elasticity depends on the strength of the interatomic bonds and composition of the material. Furthermore, it is not strongly dependent on the material's microstructure. The linear section of the stress strain curve occurs before the material breaks and represents the material’s behaviour when it is still able to return to its original shape. The modulus of elasticity therefore provides information on the elastic quality of the upper of a shoe when it is submitted to loads that are within its normal operational range, perhaps closer to those during walking.

The modulus of elasticity is found on the stress-strain curve and therefore the parameters that affect both stress and strain need to be adequately controlled. Stress is the force acting on a unit area over which the load is applied, whilst strain is the change in dimension per unit length. As can be seen from Equation 1 there are a number of inputs used to calculate the modulus of elasticity, each of which, need to be controlled in order to maintain the value of the modulus.

$$modulus\ of\ elasticity = \frac{tensile\ stress}{extensional\ strain} = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{FL_0}{A_0 \Delta L}$$

$where$:

$E = modulus\ of\ elasticity$

$F\ is\ the\ force\ exerted\ on\ the\ object$

$A_0\ is\ the\ original\ cross-sectional\ area\ through\ which\ force\ is\ applied$

$\Delta L\ is\ the\ amount\ the\ length\ of\ the\ object\ changes$

$L_0\ is\ the\ original\ length\ of\ the\ object$

Equation 1: The Modulus of Elasticity (Young’s Modulus)

Despite the clear benefit to knowing the modulus of elasticity of the materials used for shoes (since it reflects what the wearer will experience), it appears from the data provided by INESCOP, shown in Figure 137, that footwear manufactures do not regularly measure it. In order to find the modulus of elasticity and perhaps find out why this is the case, data from the tensile test was requested from INESCOP. They provided both raw data and a report (the plot form the report can be seen in Figure 138). From this plot it is apparent that instead of plotting stress and strain they instead plotted load against extension. To investigate the possible reason for this, plots were produce from the original data for load against extension and stress against extension which can be seen in Figure 139 and Figure 140 respectively.

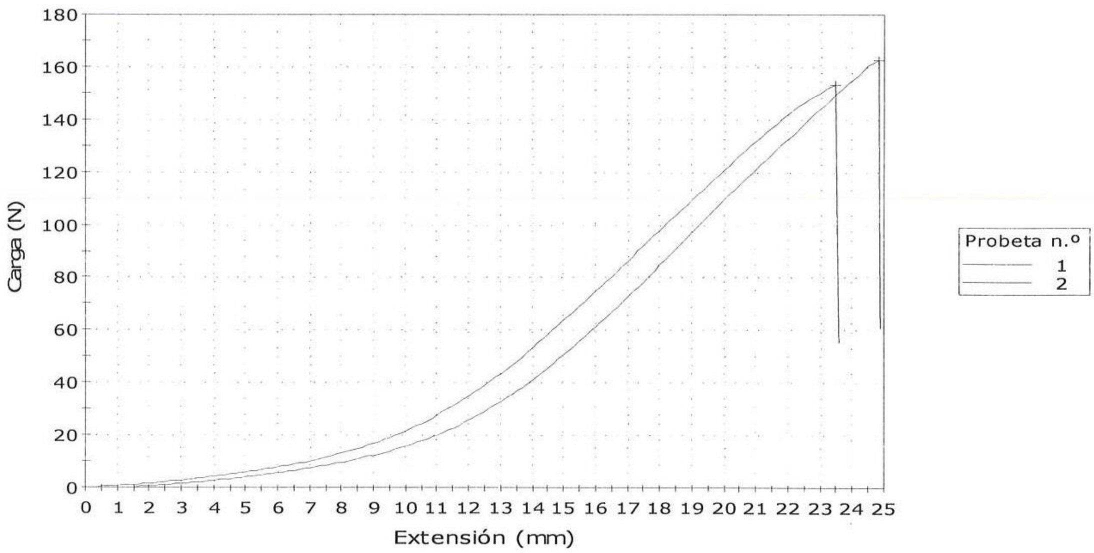

Figure 138: Plot provided by INESCOP showing the force against extension curves for two materials.

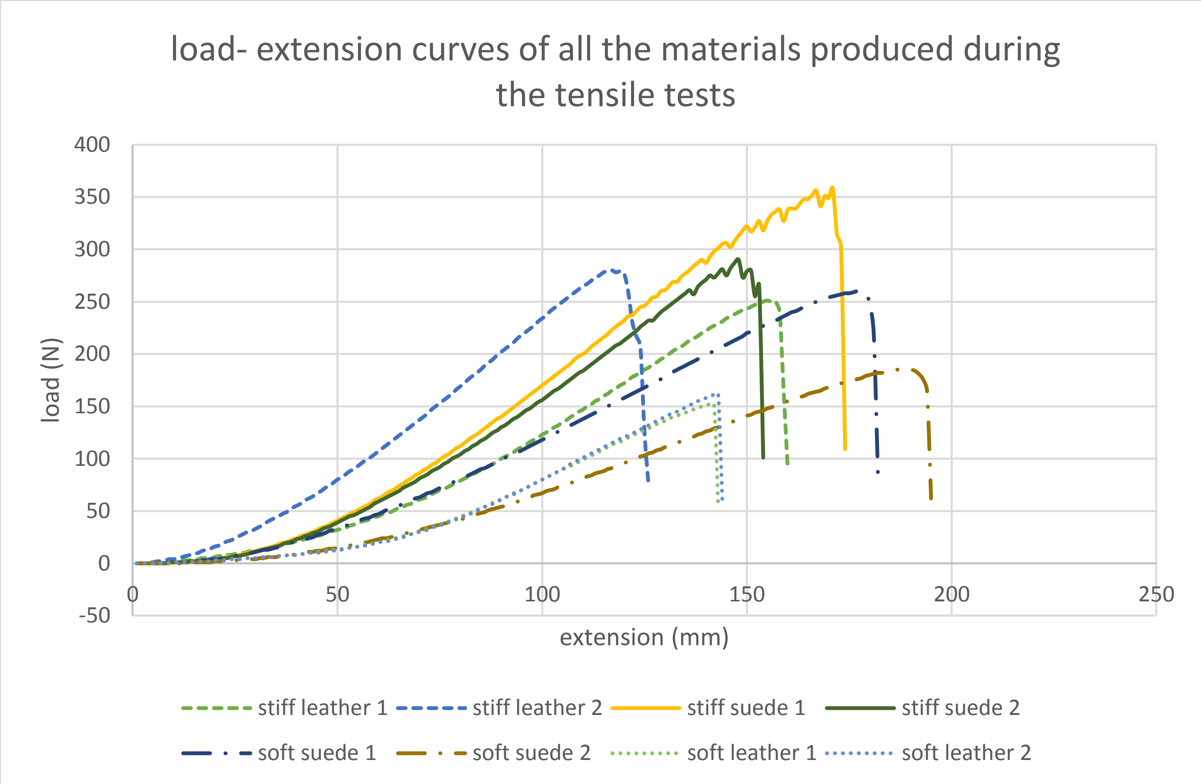

Figure 139: load- extension curve for the upper materials taken during the tensile tests

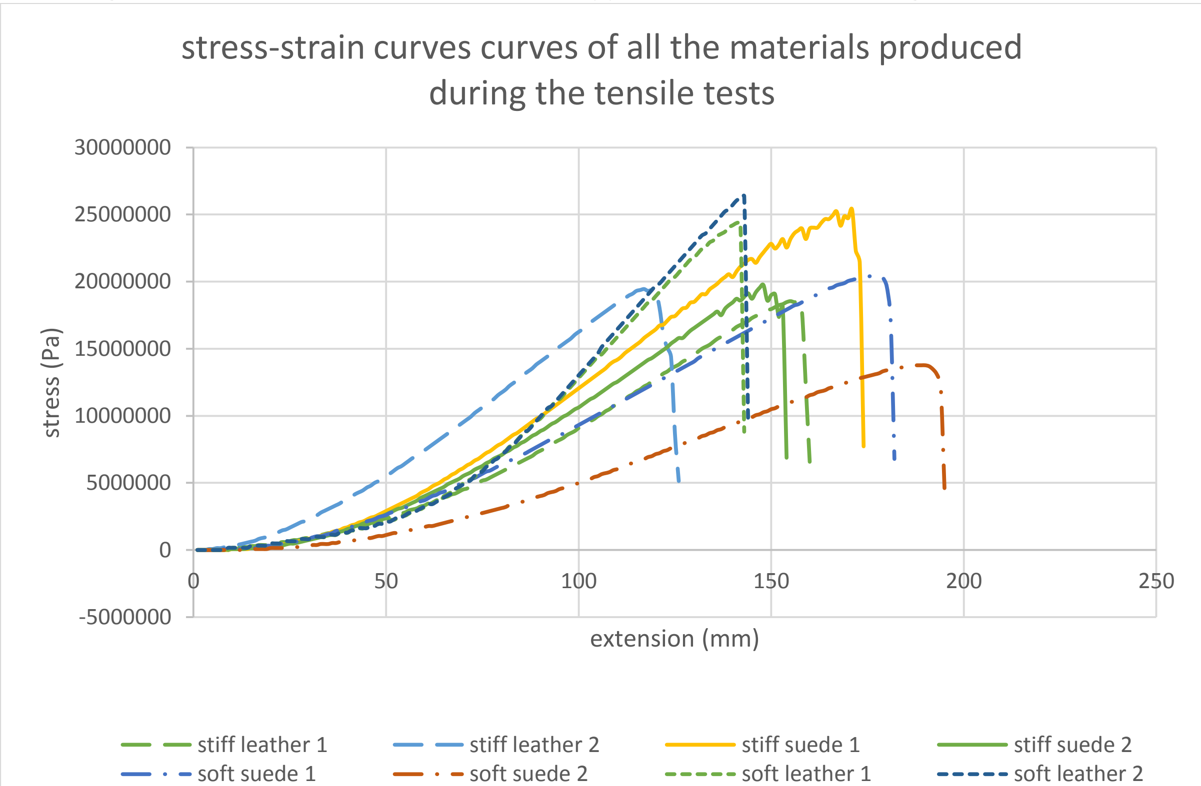

Figure 140: stress-extension curves for upper materials taken during the tensile tests

As can be seen for each material, two tests were carried out, one from each shoe. Variability between the two tests of the same material might highlight the difference between the animal hides used and/ or the variability introduced in the manufacturing process, or shows the effect of not controlling the orientation of the leather grain between test samples. Since an organic material does not have uniform strength in all directions, this could be detrimental to the test.

From the plots in Figure 139 and Figure 140 it is clear that there is little variability between stiff (calf) suede 1 and stiff (calf) suede 2 as well as the two soft (goat) leathers. However, there is relatively large variability between the two soft suede and the two stiff leather materials. The plots for the stiff suede are steeper than that of stiff leather 1 but shallower than that of stiff leather 2, indicating that the stiffness experienced by the wearer may not have been incremental, as expected. It is also apparent that the materials initially do not show a linear curve and each material starts to follow their linear period at different times. This means that for different loads the material that is showing the stiffest characteristics changes. Of all the materials the soft leather shows the steepest curve, however this exaggerated steepness is observed only in the stress-extension curve, in the load-extension curve the soft leather follows a much shallower curve. It is believed that the large difference between the two plots is due to the large difference in material thickness, for which the soft leather is less than half the thickness of the next thinnest material.

The stress-extension curve shown in Figure 140 is more closely related to the stress-strain curve normally used to test mechanical materials than the load-extension curve provided by INESCOP. As a result the specific characteristic of the material is somewhat masked in the load-extension curve, however, this is done for good reason. The materials used are biological in nature and thus there is variability between the samples. One such characteristic is the thickness of the leather. If materials are chosen on results solely from the stress-extension data then hides of different thicknesses may be used and subsequently the stiffness will also be varied despite being the same material. By using the load-extension curve the investigator is able to compare the sample of any thickness against any other material of any thickness, thus the result is more reflective of the specimen that is used on the shoe rather than a general property of the material. Furthermore, in the load-extension curve there is little to no clear period in between the elastic limit and the breaking point. This is expected given the material type and explains why it is common practice in footwear tests to report the elongation and load at failure.

These findings show a number of possible reasons why the results from the two studies in this thesis that involve material stiffness differ in their outcomes. As previously explained there are always differences between organic materials that are impossible to control. These results show that even aspects of the material that a designer may expect to be consistent change, such as the final thickness of the leather. Furthermore, these results show that the different materials were not as incremental as expected and in some cases there is crossover in the scores of the four samples from two different materials. Also, the results reveal that the materials change their behaviour relative to each other dependent upon the loading exerted on them. As a result the effective stiffness of the materials at different heel heights and shoe volumes may change as the change in the shoe design will affect the loading of the foot onto the material. All of these issues are possible reasons for the results between the two studies being contradictory of each other and highlight the problems facing future research should they use leather as their upper material.

The interactions between material stiffness and shoe volume on plantar pressure

There was a statistically significant main effect due to the interaction of material stiffness and shoe volume in the MTP1 and the MT24 regions. For the MTP1 region the soft materials and large volume shoe produced the highest plantar pressure whilst the stiff material and small volume produced the lowest plantar pressure. This shows that when the foot is more constricted by the stiffness of the material and a reduction in volume the pressure is increased. In the MT24 the soft upper shoe has both the highest plantar pressure in the largest volume shoe and the lowest plantar pressure in the medium volume shoe. Whilst all shoe stiffness's showed their lowest plantar pressures in the medium volume shoe. The changing results at the MT24 perhaps reflect the sensitivity of the forefoot to changes in its constriction. Wherein, the correct conditions will permit the presence of a transverse arch, as explained previously, which enables the offloading off the MT24. However, the problems associated to the material tests explained above and the small number of materials and volumes used prevent a more conclusive explanation.

Repeat trials

There was a statistically significant result when the plantar pressure values of the three repeat trials (medium stiffness material shoe, largest volume) were compared. The region that showed a statistically significant result was the MT24 and this occurred between the first and third trial. However, the p value was only just statistically significant ($p = 0.049$), this was only statistically significant result out of 12 tested. Similar to the previous investigation this only occurred with the first shoe, perhaps providing justification for collecting a full data set with a shoe for which the data is not required, whilst the participant is familiarised to the process and the Pedar system acclimatises to the environment within the shoe. The data for the first trial in this investigation was not used for anything other than the comparison of the repeat trials. When comparison was required between this shoe and any other, the data from the second trial was used.

The effects of changing forefoot shoe volume and material stiffness on comfort

Across all of the comfort scores there was a statistically significant reduction in comfort when the volume of the shoe upper was decreased, which confirms hypothesis three. For all questions, except those of the toe region, an increase in shoe upper stiffness also reduced comfort, thus confirming hypothesis five. In the case of the toe region no statistically significant effect was found when the upper stiffness was changed. However the toe region was the area most susceptible to changes in the shoe volume, with a statistically significant change observed between all conditions. Furthermore, the similarity between the overall comfort and the overall width comfort results perhaps suggests that width is key importance to the wearer's perception of comfort.

The only interaction between upper stiffness and shoe volume found, was for the overall shoe width comfort, whereby for all upper stiffness's a reduction in comfort occurred when the volume was reduced.

In the development of this study and subsequently the results it became very apparent that the volume of the shoe at the forefoot is very important for the comfort at the back of the heel. In pilot testing it was found that it was not possible to use the fourth volume, as originally intended, because of the pain experienced at the back of the heel. During the final tests, despite only using three volume conditions, some participants complained over discomfort at the heel which felt "like a blister was developing". This is not the first investigation to observe the increase risk of blisters due to insoles [134]. In this study some participants complain of serve discomfort whilst wearing the smallest volume shoes, since the insole for this condition was 3mm when compressed, one suggestion is that insoles should be no more than 3mm thick when compressed.

Past studies have not systematically controlled the reduction in volume at the forefoot so it is not possible to directly compare results. However, past papers have reduced the volume by changing the shape of the shoe and found that rounded toe boxes produce the least pressure on the medial aspect of the toes whilst a pointed toe box produced the least pressure on the lateral toes [236]. One would expect that a pointed toe shoe to have the least volume and therefore one could conclude that the results of the past study showed that a reduction in volume increase pressure on the medial toes and reduced it on the lateral toes. In fact past research has defined pointed shoes as narrower shoes [122]. However, the past result is opposite to that seen in the current study where a reduction in volume reduced the pressure on the medial forefoot. This serves as another reminder that neither the regions observed nor the conditions investigated should be generalised and need accurate definitions. Whilst a pointed shoe is likely to reduce the volume it also forces the toes into a point and thus creates a very different condition. Furthermore, whilst the pointed shoe does go into a point and thus the volume is smaller for the toes, this may have little to no bearing on the volume at the metatarsal heads. Due to these discrepancies, a pointed shoe should not also be defined as a narrow shoe since it is an ambiguous definition. Thus the difference observed between the results in the two studies shows differences in the effects of two unrelated shoe features on pressure.

Interactions between shoe fit and comfort score:

Since the pilot study revealed that small volumes lead to discomfort at the heel, it is unsurprising then, that the back of the heel was the primary region where discomfort was reported when the volume was reduced. In fact when the soft material was used as the upper, for both of the reduced volume conditions there was a statistically significant interaction between fit and comfort at the back of the heel. Whilst it would be expected that the softest material would be the most comfortable since if it the most malleable it is the only material to achieve a statistically significant result in these test. Showing that fit can have an effect on comfort but the shoe features ordinarily have a greater effect making the effect of fit secondary.

Despite often receiving higher discomfort scores the stiff material does not feature as a statistically significant result in the interaction tests, strengthening the argument that the small changes in the difference in circumference between the foot and last has insignificant effect on the comfort experienced when the shoe is already very uncomfortable. This suggests some degree of ceiling type effect, whereby discomfort gets no worse, and likewise comfort gets no better when volume is reduced/increased any further. However, it should be noted that there is a low participant numbers in these tests (n=11) and thus using more participants may produce a greater number of significant results.

5.8. Conclusion

This study found that for a high heeled shoe (≥55mm) increased shoe forefoot volume increased plantar pressure under the MTP1 which is contradictory to hypothesis one, and reduced the plantar pressure under the heel. The data required for hypothesis two was lost due to sensors reporting values outside of their working range. At the sole of the forefoot the comfort was reduced when the volume was reduced which concurred with hypothesis 3. An increase in material stiffness reduced plantar pressure below the MTP1 and increased in below MT24 this is the reverse of that predicted in hypothesis 4. Comfort was reduced on the sole of the forefoot when material stiffness was increased which concurs with hypothesis 5. Changes in comfort due to fit were only observed at the heel. Changes in the fit at the forefoot between the participants' produced a statistically significant difference in the comfort reported at the back of the heel.

From the results of the interactions between fit and comfort it can be concluded that forefoot girth has no significant effect on shoe comfort when the shoe is already very uncomfortable and very comfortable, and thus Hypothesis six is rejected. However, when a shoe is not regarded as either very comfortable or very uncomfortable the small differences between individuals' feet dimensions may be sufficient to affect the comfort score. This outcome perhaps reflects the lack of existing information used to formulate hypothesis six.

The insoles only change the volume of the forefoot part of the shoe, despite this it was the heel of the foot that experienced the most discomfort as a result of the changes in shoe volume. This highlights that the foot/shoe complex is a closed mechanical system and changing any feature in this system has the potential to affect any and all other features of the system. This demonstrates the need for researchers to accurately describe the conditions under which they test, including the shoes used and the feet they used for the investigations.

5.9. Limitations

What constitutes the stiffness of an upper is not well defined. Whilst individuals can easily agree after touching shoes that one is softer than the other, assigning a value to that shoe’s stiffness is not as simple. Materials, particularly organic materials such as leathers, are not consistent in their mechanical properties both directionally within a sample and across samples. As a result defining and understanding what material is being tested is difficult. Whilst material tests can be carried out it is unlikely that they will be placed into the testing device at the exact same orientation as that in the shoe and therefore may not provide the result expected. Furthermore, the standard material tests destroy the material that they test, so the tests can only be carried out after the materials have been used in the investigations. It is also clear that the current tests don’t reflect what is experienced by the wearer, for example in this study the goat leather was considered the medium stiffness material because it was easier to manipulate, flex, and stretch in your hands than the bovine leather but less so than the bovine suede. Despite this it scored higher than the bovine leather in most of the material tests. It may therefore be beneficial if future research used synthetic materials that are easy to specify and consistently manufacture, so that individual material properties can be tested and a better understanding of their effects can be developed.

Unfortunately, once all data was collected it became apparent that the scanner hadn't worked as well as expected. When collecting data the scans were quickly observed by the investigator but in later analysis it became apparent that during collection the calibration had been lost. The scanner had to be calibrated to ensure the data from each receiver was aligned. The manufacture did not provide details on how often this should be done and in fact said that if the scanner was not moved the scanner should not have to be recalibrate. As a result the scanner was only recalibrated after periods without use or if it was moved. After one calibration the alinement was only slightly but significantly out of position and this went unnoticed for a period of time, until the data was processed. It was apparent when looking at the point clouds from one perspective the alignment of the scanner was off. This change was only small, so was not picked up on the relatively quick checks made during testing. This could be seen by a step in the surface of the point cloud that did not follow the natural contour of the foot. On review of the data from the other participants it was clear that it was not just one participant and therefore all participants that had used the same calibration were removed from the data set.

5.10. Recommendations for future studies.

The variability between leather samples and differences in the manufacturing process make controlling just one characteristic of the material sample almost impossible. Whilst leathers are widely regarded as one of the best materials for shoes, it is not an ideal material for scientific testing and therefore future studies will need to take great consideration of which material they use and how this may affect results. Perhaps opting for synthetic materials may help develop our understanding of how changing the characteristics of the upper can affect its comfort and performance. This study chose leather because historically it is the material of choice, when producing the most comfortable shoes. With their ever improving development and the relative ease in which there properties can be controlled this author recommends that future studies use synthetics in order to ensure the quality of their results.

Chapter 6: Thesis Discussion

6.1. Review of thesis aims

This thesis set out to investigate how the comfort and health problems associated with high heel use could be reduced. Since high plantar pressure has been associated with health and comfort the two measurements taken were plantar pressure and comfort. From the review of the literature a number of gaps in scientific knowledge were apparent. A primary issue was that it was not clear what constitutes a “high heel”, in particular how a high heel should be characterised and at what height a shoe heel should be considered to be “high”. Previous research had investigated the effect of varying heel height but without adequate control of other footwear features that are common to “high heeled” shoes, such as upper material stiffness and volume of the forefoot area. Nor had effects of systematic increases in heel height been investigated either in isolation or in combination with the effects of other footwear design features. These failings meant that too little was understood about the relationship between heeled footwear design features and plantar pressure and comfort. To fill this void in the scientific knowledge the following objectives were established.

- To investigate the effect of an incremental increase in heel height on plantar pressure and comfort (chapter 4)
- To investigate the effect of an incremental increase in upper material stiffness on plantar pressure and comfort (chapter 4 & 5)
- To investigate the effect of an incremental decrease in forefoot shoe volume on plantar pressure and comfort (chapter 5)

To establish how these objectives could be solved a literature review was conducted which considered the approaches to measurement of plantar pressure. Whilst measures of plantar pressure are well established in footwear research, two critical questions pertinent to investigation of heeled footwear were unanswered. Firstly, it was not clear how many steps were required to acclimatise to unfamiliar footwear. Secondly, it was apparent that human gait is very variable and numerous steps are required in order to produce an average that could be used as a representative step for 'normal' gait. However, how many steps required to produce data representative of walking, in a specific shoe had not been researched conclusively. Due to discrepancies in the literature and lack of objective data on these two issues an investigation was completed to establish the number of steps required to acclimatise to unfamiliar footwear and the number steps required to produce a representative average step. To ensure valid data was collected in the footwear investigations these two questions regarding the number of steps required were answered prior to researching the effects of heeled footwear on plantar pressure, to achieve this an initial aim was:

- Produce protocol recommendations for studies that investigate how footwear design features affect plantar pressure. (Chapter 3)

6.2. Recommendations for the measurement of plantar pressure in footwear research

A new approach was implemented to determine the minimum number of steps over which Plantar Pressure data should be recorded and to establish the number of steps required to acclimatise to unfamiliar footwear. According to the data collected, the values recommended for future research studies are 30 steps for valid data, and 166 steps to acclimatise to footwear. These were upper boundaries (two standard deviations) of the highest values across all the foot regions tested and for a range of shoes and therefore are conservative recommendations.

6.2.2. Producing an average representative step

The minimum number of steps required to produce an average step was found to be 30. This is far greater than the 12 steps suggested previously, however, the past study's suggestion was based on study of the foot affected by diabetes and neuropathy [26] and only used a 20 step protocol. The small number of steps in the protocol meant that it could only have found that less than 20 steps are required due to the convergence of their data. Since, the study in the current thesis did not investigate the effects of those with injury, disability, or health concerns and the limitations of previous work have been highlighted, investigating these effects should be an objective of future research.

There was little effect due to the footwear design and thus it can be concluded that the number of steps required to produce valid plantar pressure data is not strongly dependent on the footwear. This seems unintuitive given the varied shoe designs chosen, but it perhaps reflects the ability of the foot to quickly accommodate to new positions and external constraints. The foot's ability to quickly adapt to new experiences may be limited for those that have no health conditions that inhibit sensory feedback and thus further investigations should be conducted on those who suffer from such conditions.

6.3. Heel Height

6.3.1. The effects of increasing heel height

An increase in heel height transfers the pressure from the heel to the medial forefoot, which is consistent with previous studies [10, 23, 24, 39, 42, 44]. For heels under 55m a 20mm increase in heel height will significantly increase pressure under the MTP1. For shoes that are over 55mm a significant effect can be seen with just a 10mm increase in heel height. However at the MT24 a significant effect is not seen until the heel height is at least 65mm. Despite the general agreement amongst past studies that forefoot pressures, including that of the hallux, increase with increased heel height [23, 39, 44], pressures under the hallux in the investigations conducted in this thesis were unaffected. Unlike the shoes worn in this investigation, all of the studies that showed an increase in pressure under the hallux [23, 39, 44], with increased heel height, tested shoes with a narrow toe box. The increase in pressure under the hallux may therefore be characteristic of high heeled shoes in combination with a narrow toe box. Indeed, an increase in pressure at the hallux with a more pointed toe box has been reported [236]. However, the study in this thesis cannot conclusively determine that increased pressure previously observed at the hallux is due to toe box shape because this thesis did not test shoes that had both constricting toe designs and unconstricting designs. It is therefore recommended that future research investigates the effects of toe box design on hallux plantar pressure in high heeled shoes.

6.3.2. Interactions

There were no clear interactions with heel height and materials stiffness or fit. This is likely because the effects of heel height on plantar pressure distribution and comfort were by far greater than that of material stiffness or fit. There was also a relatively small sample size. Future studies could better control material stiffness, use more participants and a larger difference in stiffness and a smaller difference in heel height. However, these results do show that heel height is much more important to determine comfort and pressure than material stiffness or small changes in fit. This may be an important consideration for designers, who need to take great consideration when adjusting the height of the heel. Whilst they can alter pressure after they change the heel it is unlikely they will be able to completely eliminate the effects of rise in heel height. Since relatively small changes in heel height have been shown to affect pressure, this result may in fact be of greater concern to shoe designers that are not working with high heels. Designers in the foot health sectors may wish to develop their understanding of the effect of changes in heel height, in their footwear sector, since small changes in pressure can be of great concern to those with health issues such as diabetes. Designers in the fashion sector are unlikely to stop making high heels due to their popularity amongst fashion conscious consumers. However, it is suggested that they aim to design shoes that are as low as possible whilst still maintaining the desired look. Focusing on concepts such as the effective heel height may aid this, as it is possible to add material below the forefoot without increasing the effective heel height, thus a high heeled appearance can be achieved whilst limiting the effect on the foot.

6.3.3. The development of a definition for high heel

In order to best define the height of a shoe's heel it is recommended that the effective heel height is used [24]. Whilst, this has been mentioned in previous works [24] the literature review and subsequent studies of this thesis have highlighted the essentiality of using the effective heel height. To fully define the heel height via the effective heel height the heel seat length, wedge angle and heel elevation must also be defined or maintained across conditions; in fact it should be the goal of the researcher to have no uncontrolled variables. However when heel height is increased, the heel wedge angle and seat length must be adjusted to ensure the wearer is still able to walk. The criteria for the changes required with heel elevation is said to be first defined by the American system [241] however this book is out of print and not available at all in the UK, reference to it was only found by this author in another book, Goonetilleke 2012 [38]. Unfortunately, Goonetilleke 2012 [38] was not published until after the shoes for this study had been requested. Similarly Goonetilleke 2012 [38], explains that with an increase in heel height the wedge angle and toe spring have to change and recommendations are presented. Since the footwear tested here predates these recommendations, values recommended by the manufacturer were used (the manufacturer has been unable to release these data). However, throughout these investigations the investigator attempted to keep as many features as possible the same and therefore when shoes were the same height their sole features were also maintained.

Past research has recommended that heels over 5.08cm should not be worn [12] as they are associated with many undesirable effects on the wearer including increased ankle plantar flexion, knee flexion, vertical ground reaction force, as well as increased heard rate and oxygen consumption. Studies have suggested heights from 50mm [35] to 95mm [7] as a "high heel", but few have provided rationale for their choice. It is apparent from the comfort and pressure data in this thesis and past work [12] that the experience of the wearer is different once the heel height is circa 50mm. Thus a definition of a high heeled shoe could be considered to be a shoe with an effective heel height of 50mm or more. However, since it is not clear from the previous study if effective heel height or an alternative definition of heel height was used, it is proposed that a more conservative effective heel height of >55mm is used as the definition of a "high heel".

Future studies concerned with the effects of high versus low heeled shoe might adopt heels of not more than 35mm for the low heel. Since a 20mm change in heel height was required to observe a significant effect on plantar pressure, a "high heel" of >55mm necessitates that a low heel is no more than 35mm.

Whilst establishing trends in pressure and comfort due to the investigated variables was one the initial purposes of this study, it became apparent that features of the foot bed should have been more closely controlled. Also, the use of organic materials for the upper could mean that there are inconsistencies between the shoes tested that were not accounted for. Future researchers can view the graphs in chapter 4 and see the curves change with heel height but they must do so whilst also considering the limitations outlined, and thus it would not be wise to draw a definitive conclusion on the effects observed from the results obtained in this study.

Tests on shoes of different heel height were carried out on a UK shoe size 5. This was for practical reasons related to shoe manufacture, but one issue is whether results are transferrable across foot sizes. A 55mm effective heel height will not have the same effect on a UK Size 3 as it does to a size 5. Since the length of a size 3 foot is approximately 2/3rds of an inch (UK shoe sizes are still based on an imperial measurement system) less than that of a size 5, in order to have a 55mm difference in height from the forefoot to the heel the midfoot would have to be at a much more steeply inclined for a size 3 than a size 5 foot. This increased incline will worsen many of the issues previously raised such as a reduced base of support, reduced moment arms at the ankle, and likely greater loading on the forefoot. Thus the heel height at which a size 3 can be considered a high heel is likely to be less than 55mm. It should be further noted that the exact dimensions of a shoe size is brand specific, so any effects of the footwear design features that are size sensitive might apply to slightly different sizes in different brands.

6.4. Shoe Volume

An increase in shoe volume increased pressure at the MTP1 and reduced it at the heel. Whilst, this may have implications for conditions such as hallux valgus which is reported as an effect of wearing high heels [10], its implications may again be of greater interest to diabetic shoe designers, since shoes for diabetics aim to reduce plantar pressure in the forefoot [120]. Little research has been conducted on the uppers of diabetic footwear with most designs opting for a loose fitting upper based on the assumption that it will not load the foot. These results show that a loose upper may in fact be making the shoe worse for the diabetic foot. However, for high heel designers the results show that a close fitting upper can help minimise the increase in plantar pressure and thus shoe designs that allow the participant greater control over the fitting of the shoe perhaps with buckles or lacing that are functional not just aesthetically pleasing, may be beneficial.

In all regions there was a significant reduction in comfort when the volume of an upper at the forefoot was decreased and of all the regions the toes were the most susceptible to changes in shoe volume. Similar results were observed in the pressure data showing that the effects witnessed in the pressure data are also felt by the participant and thus could affect their opinion of a shoe, making it an important consideration for designers.

For the regions investigated in the comfort questionnaire the only interaction of upper stiffness and shoe volume found was that of overall shoe width. For this question all upper stiffness's showed a reduction in comfort when the volume was reduced, however the size of this change was dependent on the material stiffness used. This suggests that a designer could optimise the comfort of a shoe without changing the last, but instead changing the upper material. However, this study highlighted some of the issues related to current upper material investigations, concerning the control and definition of the upper material used. Until studies are completed with these limitations resolved, it is not possible to definitively say which materials are best for particular shoe designs.

What we currently know: There is a significant interaction of material stiffness and shoe volume effecting pressure in the MTP1 and the MT24 regions. For the MTP1 region the soft materials and large volume shoe produced the highest pressure whilst the stiff material and small volume produced the lowest pressure. In the MT24 the soft shoe has both the highest pressure in the largest shoe and the lowest pressure in the medium shoe. All shoe stiffness results showed the lowest pressures in the medium volume shoe.

6.5. Upper Stiffness

6.5.1 The effects of increasing material stiffness

This is the first study to attempt to systematically change upper material stiffness across a group of shoes that are otherwise identical and investigate the corresponding changes in plantar pressure and comfort. There is therefore no past research to draw direct comparison to the results. An increase in upper material stiffness increased pressure under the MTP1 and reduced pressure under the MT24 when heel height was also systematically increased (chapter 4).

Between the two high heel investigations in this thesis there was contradictory data supporting the existence of frontal transverse arch. In chapter 4 the possibility that the stiffer material encourages a more pronounced frontal transverse arch was discussed whilst in chapter 5 there was no evidence of this. Possible reasons for this discrepancy between the studies are; in order to encourage the more pronounced arch, a higher level of loading is required. This increased loading would have been produced by the increased heel height in chapter 4, but not in chapter 5 where all heel heights were the same. Alternatively the differences in the upper designs between the two studies resulted in the shoe used in chapter 4 being of a more constrictive nature, or the change in contact area between the two shoe designs focused the pressure in different regions. Nonetheless, in chapter 5 there was an increase in pressure at both the MT24 and the hallux with increased material stiffness. Thus, the pressure of the forefoot can be increased by both material stiffness and heel height however their effects on pressure vary for each separate region of the forefoot.

This variation is most likely because of the much higher increase in pressures generated by the increased heel height compared to material stiffness.

If increasing shoe volume and reducing material stiffness both reduce the physical constraints on the foot, it could be argued that the effect of changing the material stiffness and volume are effectively the same. The grounds of this argument are that a material that is soft is easily manipulated and thus can provide a greater volume for the foot. The effects of changing volume are greater; this is likely because the variation in volume due to the material stiffness is less than that when the volume is altered, such as by adding an increasingly thicker insole. As a result the effects due to volume are quite different to that of material stiffness and perhaps the theory of the transverse arch considered in chapter 4 could still be argued. In chapter 4's transverse arch theory the transverse arch is made more pronounced, which results in the increase in pressure at the MTP1 and the reduction at the MT24. Thus, from the two studies a conclusion could be drawn that a well-fitting shoe with an upper that both provides adequate room and holds the foot correctly, will reduced pressure at the MTP1 and increase it at the MT24. However, when the pressure is increased at the MTP1 (which can be achieved by heel height or using very constrictive shoes), the transverse arch is encouraged and thus the pressure at the MTP1 is increased and reduced at the MT24.

For a transverse arch to occur, there needs to be an increase in the loading of the internal structures of the foot which might perhaps explain why narrow toe boxes are associated with Morton Neuroma [4]. For heel height there is a large range from flat to an almost vertical foot position can be used. For the constricting features of the shoe such as volume and material stiffness, a threshold beyond which the shoe becomes impossible to wear exists (as observed during the pilot study). These thresholds can either be because the foot will not fit or there is great discomfort and these occur after relatively small changed to the shoe design. Whilst this study has shown that an increased transvers arch may occur, it cannot conclusively confirm what would make the arch to rise, what effects this has on the foot and gait, nor exactly how this happens. Therefore these are all areas that need to be investigated in future research.

6.5.2. How the material qualities may have affected the results

Despite there being many occasions across the studies in chapter 4 and 5 that there was a significant difference in pressure between the medium material and the stiff materials, there were only two results that showed a significant difference between the soft and the medium materials. This may show that there is a particular stiffness above which pressure is significantly increased. However, given that there is some inconsistency between the material stiffness (as shown be the material tests conducted by INESCOP in the previous chapter), this is not proven in this thesis. Additionally, it is also possible that the pressure increases linearly with material stiffness, but because there was not a linear increase in material stiffness this was not fully tested in this thesis. The studies in this thesis have highlighted how important controlling all aspects of the shoe design (in this case material stiffness) to a fine degree of accuracy is to the final results.

It is clear from this experience that controlling the properties of footwear that is produced for research is essential if the research is to be allowed to systematically investigate how footwear features affect feet. During the course of this thesis the commercial partner endeavoured to support the project requirements, but the footwear industry, especially for mass manufacturing, is not aware of the importance of controlling the design and manufacture process for research purposes. Throughout the PhD, significant difficulties were encountered in explaining the concepts behind the research designs, the absolute need for maintaining the independent variables, controlling confounding design variables, and making footwear to exact specifications. Indeed, there were many practical difficulties in the project in this respect, including many months of delays and many shoes produced (at significant cost) that were unusable in a research context. Ultimately this affected the progress of the research. Managing communication between research partners and manufacturers should be a priority for future research studies.

6.7. Conclusion

It is recommended that the period required to acclimatise to unfamiliar footwear is 166 steps per foot and that no fewer than 30 steps of PP data should be recorded. An increase in heel height will reduce the pressure at the heel and increase it at MTP1 and MT24 whilst also reducing comfort.

The investigations in this thesis showed that an increase in heel height transfers the pressure from the heel to the medial forefoot. An increase in heel height from 35mm to 75mm will increase pressure at the MTP1 (46%) and MT24 (33%) but reduce it at the hallux. It was recommended that shoes with an effective heel height of over 55mm should be defined as a high heel and a low heel shoe should not have an effective heel height of more than 35mm.

Reducing the volume of a shoe will decrease pressure at the MTP1 and increase it at the heel. These changes will also result in a reduction in comfort scores across the whole shoe. There is an interaction between the volume and the material stiffness of a shoe which can affect the pressure at both the MTP1 and MT24. However the effects of the material stiffness are also dependent on the height of the shoe being tested. Unfortunately, clear trends due to material stiffness could not be developed due to the limitations of the materials used within this research.

6.8. Limitations

All individuals in the studies presented here had the same foot size (within each study). However, despite wearing shoes which are predominately defined by their length, participants who wear the same shoe size can still have variations in longitudinal foot measurements. Since shoe sizes are graded, in the UK, by variations of a third of an inch (8.45mm), a variation of a this scale can also exist between the wears of the same shoe size. Furthermore, there is also variation in the sizes of people's feet in medial/laterial and inferior/superior directions. For example despite having the same size feet, one person may have longer toes than another person. When someone has longer toes than another, it is also likely that the location of the MTP joints will be more proximal. Such movement in the location of the MTP joint would result in the alignment of the joint and features of the shoe changing. This could be of particular interest in high heel studies where the midsole angle rises steeply from the approximate location of the MTP joint and misalignment may have an effect on pressure and comfort, however further research is required to distinguish the significance of this. Thus, one limitation is that how the choice of shoe size studied and variations between individual participants in foot size and shape affect footwear fit and performance is not known.

As previously discussed in the literature review of plantar pressure, the loading on the plantar surface consists of both shear and plantar pressure, and only the latter can currently be measured inside shoes. This is a limitation that all in shoe gait studies experience and will continue until developments have provided new sensor technologies. Furthermore, the pressure measurement equipment currently available can measure either the whole plantar surface when barefoot (which prevents any evaluation of footwear effects), or at pressure discrete locations within the shoe where pressure sensors are located. The in-shoe method not only requires the location of interest under the foot to be decided before testing, it may introduce error into the data collection. This error is twofold, firstly the sensors are likely to move from the initial or preferred measurement location as the participant walks. Secondly, they introduce an 'alien' object into the shoe that may change the vertical and shear pressures loading by virtue of the space it occupies. Therefore, in studies in this thesis the measurement approach inevitably disrupts the pressure distribution being measured. However, this is an issue for the wider foot biomechanics community and not specific to this study. .

Appendices

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