An investigation into the effect of customised insoles on plantar pressures in people with diabetes

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Abbreviations

- DM = Diabetes Mellitus
- DF = Diabetic Foot
- DFU = Diabetic Foot Ulcer
- PP = Peak Pressure
- PTI = Pressure-Time Integral
- MPJ = Metatarsophalangeal Joint
- MTH =Metatarsal head
- BMI = Body Mass Index
- EMG = Electromyography
- ROM = Range of Movement
- FEM = Finite Element Modelling
- CAD = Computer Aided Design
- CAM = Computer Aided Manufacture
- SEM = Standard Error of Measurement
- ICC = Intraclass Correlation Coefficient

Abstract

Introduction

High plantar pressures have been shown to be a key risk factor for foot ulceration in people with diabetes. Consequently, patients are often prescribed insoles designed to reduce pressure. New technologies, such as plantar pressure measurement devices and 3D foot scanners, have the potential to improve insole design. However, it is not clear to what extent such technologies are currently being used by clinicians, nor which other factors influence clinical decision making in the prescription of insoles. Furthermore, there has been minimal previous research designed to understand how best to use technology to improve insole design for patients with diabetes.

Methods

This thesis comprises four separate studies: a first qualitative study aimed at understanding the factors influencing practitioner decision making and the current role of technology. Three other quantitative studies were then performed to help understand the potential role of technology in designing insoles for medium-risk patients with diabetes and neuropathy. For each of these three studies, individually customised insoles were manufactured for every patient using CAD/CAM technology and data on both plantar pressure and foot shape. The first study investigated the reproducibility of plantar pressure collection in patients with diabetes and neuropathy while wearing the customised insoles, while the second investigated the effect of systematically varying two insole design features, metatarsal bar position and cushion material, on plantar pressures. In the final study, associations were investigated between changes in plantar pressure with different customised insole designs and specific structural and biomechanical foot characteristics of each participant.

Results

The findings of the qualitative study suggest that current clinical practice is based on training but that it develops in time based on practitioner's clinical experience. Technology is not normally used because the data is considered too complex to use and interpret. However, practitioners agreed that they would use technology that is more user-friendly and focused on improving patient outcomes.

The first quantitative study showed a relatively high level of pressure variability (up to 55 KPa under metatarsal heads) which we suggest is a characteristic of patients with diabetes and neuropathy. The second quantitative study showed that customised insoles which incorporate both a metatarsal bar and cushioning materials in front of the bar are effective in reducing peak pressures (PP). However, the optimum design was that which incorporated a combination of poron (cushioning material) with a metatarsal bar, located distal or on the point of PP. In the final quantitative study, specific individual characteristics which predicted PP changes were identified, such as tissue stiffness and joint range of movement (ROM). Based on these findings, some tentative recommendations for insole prescription were suggested. For example, to reduce PP under the 1st metatarsal when high tissue stiffness is present use a metatarsal bar just behind the PP combined with poron if there is a low range of movement of the 1st metatarsophalangeal joint. But if there is a high range of movement of the 1st metatarsophalangeal joint, a distal metatarsal bar with Poron should be used.

Conclusion

Taken together, the results of this work show that practitioners are willing to embrace more technology within their clinical practice and that it could be used to improve the efficacy of insoles designed to reduce plantar pressures for people with diabetes.

1 Introduction

1.1 Diabetes

Diabetes mellitus (DM) is a condition characterised by high blood glucose levels, which is associated with the risk of developing severe co-morbidities and complications, including heart disease, stroke, blindness, kidney disease, nerve damage, and foot complications (van Acker *et al.*, 2014). There are two main types of DM, type 1 and type 2. Type 1 DM typically affects patients earlier in life and is a complex process whereby genetic and environmental factors produce an autoimmune response, leading to the destruction of pancreatic β-cells within the islets of Langerhans, resulting in an absolute insulin deficiency (Forbes&Cooper, 2013, Tamayo *et al.*, 2014). In contrast, type 2 DM tends to affect people later in life and is characterised by a decline in pancreatic islet secretory function on one hand and tissue insulin resistance on the other (Forbes&Cooper, 2013). This is the most common type of DM and has become a major global public health problem, particularly in low and middle-income countries (Bi *et al.*, 2012).

1.1.1 Complications and physiological changes associated with diabetes

The prevalence of DM is increasing globally (Zimmet *et al.*, 2014) and consequently, the number of associated complications is also set to increase. The main complications associated with this disease include nephropathy, retinopathy, cardiovascular disease, peripheral arterial disease and peripheral neuropathy. Diabetic nephropathy is the most frequent cause of renal failure in the developed world (Forbes&Cooper, 2013, Tamayo *et al.*, 2014). It is characterised by the presence of proteins in the urine due to a deterioration of kidney function (nephropathy), which progresses over a long period of time, often over 10 – 20 years. Once nephropathy is established, typically most patients experience an increase in blood pressure, which itself is a major risk factor for diseases such as stroke and heart attacks (Forbes&Cooper, 2013).

Diabetic retinopathy is also a frequent complication associated with diabetes and is the most common cause of acquired blindness in the western world (Forbes&Cooper, 2013, Tamayo *et al.*, 2014). It is characterised by a range of lesions within the retina and develops over many years, with almost all diabetic patients exhibiting some degree of

retinopathy after 20 years of the disease (Forbes&Cooper, 2013). There is a close association between diabetic retinopathy and diabetic nephropathy.

Cardiovascular disease accounts for more than half of the mortality of the diabetic population. Interestingly, someone with diabetes is just as likely to have a heart attack as a non-diabetic with a previous history of heart attack, and three times more likely than the general population (Forbes&Cooper, 2013). The mortality derived by this complication represents more than half of the mortality seen in the diabetic population. In addition, peripheral arterial disease is characterised by several functional abnormalities of the microvasculature, which lead to capillary hypoperfusion and impaired development of collateral vessels, consequently, resulting in delayed, or even impaired, wound healing (Brownrigg *et al.*, 2013). Furthermore, those with diabetes may experience peripheral neuropathy which is defined as "symmetrical, length-dependent sensorimotor polyneuropathy attributable to metabolic and microvessel alterations resulting from chronic hyperglycaemia and cardiovascular risk covariates" (Tesfaye *et al.*, 2010). The normal development of this complication starts in the toes and gradually moves proximally. Numbness, cramps or deep pain are the most common symptoms and are generally worse at night. Initially, it will affect sensitivity and thermal sensation, then in the later stages, will progress to alter muscle and motor aspects of the lower limbs (Singh *et al.*, 2014).

1.1.2 Prevalence and cost of diabetes

The prevalence of DM has been increasing exponentially over the last few years. The International Diabetes Federation (IDF) predicted a worldwide prevalence of DM in 2013 to be 382 million (the figure previously expected for 2030) and that by 2035, this number would increase up to 600 million (Rayman, 2010). In the UK, more than 1 in 20 people suffer from DM (both diagnosed and undiagnosed). In 2011, there were 2.9 million diagnosed worldwide with DM and the average prevalence of this disorder was 4.45%, with 10% of adults with DM diagnosed as type 1 and 90% with type 2 (Kurup&Thomas, 2013). Focusing on the trends for each type of DM, serious and disturbing changes between the ages of disease presentation have been observed. For type 1 DM, incidence has been rising during the past decades and if this trend is maintained, the number of new cases in European children younger than five years will double by 2020, and prevalence

of cases in individuals younger than 15 years will rise by 70% (van Belle *et al.*, 2011). Type 2 DM was traditionally a disorder of adults and elderly people, however, it has become more common, not only in young adults but also in adolescents and children, probably due to obesity as a result of bad life habits such as diet and a sedentary lifestyle (Zimmet *et al.*, 2014).

DM has become a serious global problem. Asian countries have high rates of DM prevalence and compared with Western populations, Asians develop DM at younger ages, at lower degrees of obesity, and at much higher rates given the same amount of weight gain (Chan *et al.*, 2009). Furthermore, more than 75% of the people with this disease live in low-income and middle-income countries (Federation, 2012), representing a significant health challenge due to the lack of access to treatment because of their country's lack of resources. Therefore, there will be an increase in the risk of premature morbidity and mortality in these countries, with a subsequent increase in treatment costs for these patients.

This increase in DM prevalence has been reflected in the health care systems expenditures. In 2010, global health expenditure attributable to DM was estimated to be US$376 billion (12% of all global health expenditure). Moreover, by 2030, global health expenditure attributable to DM is expected to reach between $490 billion and $893 billion, which represents an increase of 30 – 34% from 2010 (Zimmet *et al.*, 2014). However, this expenditure varies hugely by region. For instance, more than 90% of global health expenditure on DM is in the world's richest countries, 57% in North America, 28% in Europe, and 10% in the western Pacific (Zimmet *et al.*, 2014). The direct and indirect costs associated with DM management in the UK currently stands at £23.7 billion per annum (Kurup&Thomas, 2013). This increase in DM-related expenses can be explained by the increased prevalence in the younger population, which leads to a longer evolution of the disease and therefore, more frequent, complex and serious complications which require hospital treatment.

1.2 Diabetic foot syndrome

One of the most serious and disabling diabetic complications is diabetic foot (DF). The World Health Organization (WHO) defines the DF as "The foot of diabetic patients

that has the potential risk of pathologic consequences including infection, ulceration and or destruction of deep tissues associated with neurologic abnormalities, various degrees of peripheral vascular disease and / or metabolic complications of DM in the lower limb" (Al Musa, 2013).

The DF is characterised mainly by the convergence of two of the most common consequences of DM, neuropathy and peripheral vascular disease. More than half of diabetic patients who have been suffering from the disease for 15 years or more present with diabetic neuropathy (Boulton, 2010). On the other hand, peripheral vascular disease affects 8 – 13% of people with diabetes (Abbott *et al.*, 2005), being present in most diabetic individuals who have had DM for more than 25 years. Moreover, in the presence of neuropathy, there is a lack of protective sensation that will increase the likelihood of ulcer formation and it has been shown that high plantar pressures are highly associated with skin breakdown and ulceration in people with DM and peripheral neuropathy (Lott *et al.*, 2007). Also, with regard to equal occlusive arterial damage, a person with diabetes will develop distal ulcers or gangrene in up to 40% of cases, while in patients without diabetes this complication will appear in 9% of the cases (Kannel, 1994). Consequently, when these two conditions are present at the same time, they lead to DF syndrome and also predispose the patient to ulcer formation.

1.2.1 Diabetic foot ulceration: the main complication of the DF

A diabetic foot ulcer is defined as "any necrosis, gangrene, or full-thickness skin defect occurring distal to the ankle in a diabetic patient" (Schaper *et al.*, 2012). Ulcers act as an entry for microorganisms that may lead to infections, leading to severe complications such as partial foot amputations, or, in the most severe cases, limb loss (Barshes *et al.*, 2013). Furthermore, skin changes in diabetes may increase the risk of developing an ulcer (Hashmi *et al.*, 2006, Hsu *et al.*, 2009, Pai&Ledoux, 2010, Chao *et al.*, 2011, Sun *et al.*, 2011). People with this disease often have impairments in their immune system response, with a reduced ability to recruit inflammatory cells to damaged tissues, delayed wound healing and increased risk of infection (Leung, 2007).

1.2.2 Prevalence and costs to society of diabetic foot syndrome

The worldwide incidence of DF varies between 0.5 and 3% per year, with 25% of patients with DM suffering an ulcer at least once in their life (Boulton, 2010). DF ulceration represents a major medical, social and economic problem all over the world. Complications of foot ulcers are the leading cause of hospitalisation and amputation in diabetic patients, accounting for more hospital admissions than any other long-term complication of diabetes, resulting in increased morbidity and mortality. Annually, people with diabetes who also have neuropathy will develop an ulcer in 7 – 10% of cases (Hashmi *et al.*, 2006, Rathur&Boulton, 2007, Lepantalo *et al.*, 2011), whereas those with additional risk factors, such as peripheral vascular disease, foot deformity, previous ulcers or previous amputation, this rate increases to 25 – 30% (Lepantalo *et al.*, 2011).

Regarding the UK national health system (NHS), this complication entails an increase in the expenditure and number of patients to be treated. The mean duration of DF patient's hospitalisation is 59% longer than a patient with another disease (Ramsey *et al.*, 1999). Also, there is a high impact on the patient's quality of life after being diagnosed with DF syndrome (Garcia-Morales *et al.*, 2011). Major amputation will be needed within one year in 5 – 8% of patients with diabetic ulcers (Lepantalo *et al.*, 2011), and of all amputations, 85% are preceded by a foot ulcer which subsequently deteriorates to a severe infection or gangrene (Rathur&Boulton, 2007, Lepantalo *et al.*, 2011, Bortoletto *et al.*, 2014). Studies from the UK have shown an increase in amputations in the last decade and it is estimated that 50% of non-traumatic amputations in hospitals in developed countries are due to DF (Carmona *et al.*, 2005). Also, the rate of lower limb non-traumatic amputation is between 10 and 20 times greater in patients with DM (85%) when compared to patients without this disease (Aragon-Sanchez *et al.*, 2009). Survival after amputation is lower in diabetic patients than in other amputees, being 40 – 50% between 3 and five years after the intervention. Furthermore, cardiovascular and respiratory complications are the leading causes of mortality in patients with DM and previous amputation (Aragon-Sanchez *et al.*, 2009, Aragon-Sanchez *et al.*, 2010).

With regard to the UK, 20 – 40% of healthcare resources spent on diabetes are related to the diabetic foot (Lepantalo *et al.*, 2011). The total direct cost to NHS for DF complications was estimated to be £1.61 billion, which is approximately 10% of the total

annual direct cost associated with DM, equivalent to about £1 in every £175 spent by the NHS in England. Altogether, total expenditure on healthcare related to foot ulceration and amputation in diabetes in 2010 – 2011 in England is estimated at £580.5 million (Kerr *et al.*, 2014). This cost is primarily for outpatient expenditure, increased bed occupancy and prolonged stays in hospital (Kerr *et al.*, 2014, van Acker *et al.*, 2014). However, ulceration and amputation also entail costs to individuals and their families through lost working days, reduced mobility and travel to surgeries and clinics (Kerr *et al.*, 2014). The cost of treating DF ulcers increases as the severity of ulcers increases. Moreover, patients with both infection and peripheral vascular disease reported a longer hospital stay, a higher use of antibiotic therapy and more inpatient and outpatient care than patients without this complication (van Acker *et al.*, 2014). The serious consequences of this complication added to the high costs to the NHS stress the need for enhanced management and preventative strategies.

1.2.3 Overview of the thesis and the SMARTPIF project

The DFU is a disabling complication for patients and a burden for the NHS. Given the costs, reduced quality of life and risk of foot amputation, there is an urgent need to understand how to manage diabetic foot syndrome more effectively. Therefore, the aim of this thesis was to explore different concepts within the context of diabetic foot syndrome. The research was funded by a larger 7th Framework European Union project named "SMARTPIF" (Smart tools for the Prescription of orthopaedic Insoles and Footwear).

The purpose of SMARTPIF was to enhance the practice of orthotic footwear and insoles prescription through the development of a set of technological devices and computer tools that would facilitate effective therapeutic prescription. It was envisaged that this set of tools would allow a prediction of the pressures experienced by the foot during a gait cycle and also provide software which would automatically select an appropriate shoe/insole. In addition, the project aimed to produce visualisation software tools which could enable the patient to choose a shoe before manufacture. The idea was to develop the possibility for patients to *virtually* try-on the selected shoes using augmented reality techniques through a virtual mirror, without having footwear stocks

available at the podiatrist's consulting office. Overall, there were four specific objectives for the full SMARTPIF project, these were to:

1. collect morphological and biomechanics data on the feet of individual patients
2. predict foot pressure during gait for different footwear designs
3. integrate the pressure predictions with easy to operate insole design software
4. enable patients to try-on in a virtual way their footwear choices

The University of Salford's role in the SMARTPIF project was to collect the morphological, biomechanical and pressure data from a cohort of medium or high-risk patients (objective 1). An aligned objective was to obtain insight into the factors which influence practitioner prescribing practices, and also the current role of technology in day to day clinical practice.

The SMARTPIF project has provided a base framework for the different studies presented in this thesis. However, the remit of this funded project was very broad and did not specify which patient group should be investigated, nor did it specify the precise nature of the research. This gave the freedom to shape the project in a direction that fitted the author's professional experience as a podiatrist and which also answered important scientific questions on insole design. I first performed a literature search in order to identify a medium or high-risk population who would benefit from wearing customised insoles. The target population chosen was patients with diabetes and neuropathy, given the serious and disabling complications that this disease entails. As a podiatrist, I have always worked with patients with diabetes and witnessed the serious impact that ulceration and/or amputation has on their quality of life. Prevention is the key approach to avoid ulceration, and insoles are the most common preventative measure. However, there is little evidence and no consensus on the best insole design approach for ulcer prevention. This lack of research was the main motivation for me to embark on this PhD.

Once the target population had been identified, I performed another literature search on the insole designs to be tested. I then developed a specification for the data which needed to be collected and also for the data collection protocol. I performed all data collection, processing and analysis independently at the University of Salford. Based on these data, it was possible to develop a set of studies focusing on the clinical management and insole design for people with diabetes within the context of this

externally funded project. In total, there are four separate studies completely independent from the EU project that conform this PhD. The first, a qualitative study, focused on the different factors that influence clinical decision making and, more specifically, the role of technology within the current clinical practice and how it could enhance orthotic prescription. This was followed by three biomechanical studies examining different aspects of insole design and plantar pressure measurement.

Due to the different nature of the qualitative and quantitative work, a separate literature review has been presented for each aspect of the work. Chapter 2 provides an overview of the current clinical management of the diabetic foot syndrome, followed in Chapter 3, with a more in-depth review of the pathogenesis, key risk factors and preventative strategies for diabetic foot ulceration. Chapter 4 describes the qualitative study which focused on gaining an improved understanding of current clinical practice and the role of technology. One of the conclusions of this work was the need to enhance technology to be more usable in current clinical practice. Following on from this idea, the subsequent chapters describe three quantitative studies which examine different aspects of pressure measurement and the use of technology to design and prescribe insoles for people with diabetes.

2 Literature review - Section I: The clinical management of diabetic foot syndrome

The diabetic foot is a serious complication that requires a proper professional management and prevention. This section presents a detailed literature review about how clinical practice should be, and the trends it presents. However, although there are general guidelines for some aspects of the clinical practice, there is a lack of publications about real influences and trends in clinical practice. Moreover, practitioner's decisions tend to be based on experience and personal training rather than standardised guidelines.

2.1 Current practice clinical decision-making

Diabetic foot syndrome entails different serious complications, such as neuropathy, peripheral arterial disease, retinopathy or nephropathy. These complications put patients on different levels of risk of serious consequences such as foot ulceration, lower limb amputation or, in the most severe cases, death. Accordingly, interventions should offload high pressures, with the aim of preventing ulcer formation. Generally, insoles are prescribed by podiatrists to these high-risk patients; however, there is no clear algorithm for the construction of optimal foot orthoses. There are national guidelines that recommend that high-risk patients, such as diabetics, routinely see podiatric physicians. American Diabetes Association guidelines recommend foot screening for all diabetic patients at least every 12 months (Boulton *et al.*, 2008), whereas those at greater risk for serious foot problems should visit podiatric physicians an average of 3.7 times a year (Gabbay *et al.*, 2011) so that they can be assessed and prescribed preventative insoles when necessary. However, this is not an easy task, which if not carried out appropriately, could increase the risk of ulceration.

Since Merton Root (1994) introduced the functional foot orthosis in the 1950s, many modifications and new techniques have been proposed to advance his original ideas. In addition to variations in the basic design of foot orthoses, numerous materials are used in the manufacturing process and foot orthoses can be manufactured in many different ways. Practitioners generally manufacture the orthoses themselves or use a commercial orthotic laboratory. Furthermore, there has been an increase in the use of

prefabricated foot orthoses given the lack of publications showing that customised insoles achieve better results than those which are prefabricated (Paton *et al.*, 2012). Given the huge amount of choice when prescribing insoles, and the important risks if this task is not performed properly, a better insight of the process followed by professionals when treating these medium and high-risk patients is needed.

2.1.1 Patient assessment

Clinical guidelines for diabetic foot care state that "all diabetic patients should be examined at least once a year for potential foot problems, and patients with demonstrated risk factor(s) should be examined more often (every 1 ± 6 months). The absence of symptoms does not mean that the feet are healthy since the patient can have neuropathy, peripheral vascular disease or even an ulcer without any complaints. The feet should be examined with the patient lying down and standing up, and the shoes and socks should also be inspected" (Apelqvist *et al.*, 2000). The steps taken should address the various aspects as detailed in Table 2.1.

History	Previous ulcer/amputation, previous foot education, social isolation, poor access to healthcare, barefoot walking
Neuropathy	Symptoms such as tingling or pain. Loss of sensation
Vascular status	Claudication, rest pain, pedal pulses, discoloration
Skin	Colour, temperature, oedema, nails, ulcer, callus, dryness, cracks interdigital maceration
Bone/joint	Deformities or bony prominences. Loss of mobility
Footwear/stockings	Assessment of both inside and outside

Table 2.1: Different aspects of the assessment of a patient with diabetes

Once the history is fulfilled, and before prescribing an insole, a biomechanical evaluation of the foot and ankle is required to identify the key design features to include. Podiatrists, the main profession managing DF in the multidisciplinary teams, base their biomechanical evaluation of the foot and ankle on the description provided by Root *et al.* (1994), "estimating" rather than measuring foot or limb position and motion (Jarvis *et al.*,

2012). In addition to their static assessment, podiatrists conduct a dynamic gait assessment focusing on observation at key events of the gait cycle (Jarvis *et al.*, 2012).

Podiatrists perform multiple clinical tests and measurements of the joints of the foot and leg (knee, ankle, subtalar, and metatarsophalangeal joints), both non-weight bearing and weight bearing. This is performed to identify if there is any alteration on the range of motion or alignment that can affect gait or can increase pressure (Tollafield, 1995). The assessment process is complex and is influenced by many factors, including national or local professional knowledge, clinical experience and practical constraints (time available for an assessment, the range of orthotic prescriptions available to a clinician and the particular profile of patients the clinician sees in their practice) (Jarvis *et al.*, 2012).

Once the podiatrist has assessed and diagnosed the patient, a target for the treatment is set that will include the use of insoles. Clinicians must take into consideration the potential effects of many different factors when designing an insole; if not carried out appropriately, this difficult task may increase the risk of ulceration. To prevent ulcers, offloading insoles are normally prescribed by podiatrists to diabetic patients with neuropathy, as high peak pressures have been shown to predispose ulcer development (Paton *et al.*, 2011, Patry *et al.*, 2013). There is some research that supports the use of a variety of designs for the foot affected by diabetic complications, mainly with the aim of reducing the increased foot pressures (Hodge *et al.*, 1999, Bus *et al.*, 2004, Mueller *et al.*, 2006, Guldemond *et al.*, 2007, Cheung&Zhang, 2008, Stolwijk *et al.*, 2011). Up to 40% foot pressure reduction can be achieved providing protective benefits (Albert&Rinoie, 1994, Guldemond *et al.*, 2007). There has also been some attempt at evaluating different materials (Fauli *et al.*, 2008, Healy *et al.*, 2012).

In the literature, the main aim of insoles for patients with diabetes is PP reduction (Hodge *et al.*, 1999, Bus *et al.*, 2004, Mueller *et al.*, 2006, Guldemond *et al.*, 2007, Cheung&Zhang, 2008, Stolwijk *et al.*, 2011). Different insole designs and materials have been tested in order to establish their effect on PP, and a reduction of these is classified as a good insole performance or a positive response to the insole. Interestingly, Kang *et al.* (2006) found a significant correlation between peak pressure reductions and the corresponding decrease in pain levels on the subjects tested. Accordingly, in patients with

diabetes and neuropathy who cannot feel pain, a PP reduction would indicate a decrease in pain and its cause. It could be therefore considered as a positive response to the insole.

Insoles are often prescribed to patients with similar conditions, however, not all of these patients have a positive response to the orthotics. Research has demonstrated considerable variability in the degree of plantar pressure reduction across different individuals (Bus *et al.*, 2004, Tsung *et al.*, 2004, Kang *et al.*, 2006). This variation on peak pressure reduction could have an influence on the different clinical responses to insoles experienced by similar patients. Accordingly, when a pressure reduction is achieved, the patient had a positive response to the insole. On the contrary, if there is no pressure reduction, or there is an increase of pressures, the patient had a negative response. This approach was taken in the final quantitative study (Chapter 8) to classify participants as responders and non-responders (section 8.6.1).

The main goal of preventative insoles prescribed for people with diabetes is pressure offloading, so the most reliable method to check if insoles are effective is through pressure measurement devices, which are normally used in research. These pressure devices have shown that insoles prescribed are an effective approach to pressure offloading (Ashry *et al.*, 1997, Postema *et al.*, 1998, Bus *et al.*, 2004, Hsi *et al.*, 2005, Mueller *et al.*, 2006, Owings *et al.*, 2008, Redmond *et al.*, 2009, Koenraadt *et al.*, 2012, Paton *et al.*, 2012, Ibrahim *et al.*, 2013). However, these new technological approaches are not commonly used in clinical practice due to high costs and their use is time-consuming and complex (Williams *et al.*, 2016). Therefore, as there is no quantitative approach to measuring the outcome of prevention using insoles, a better understanding of how clinicians follow this assessment, prescription and outcome measure is needed.

2.1.2 Podiatrist's and orthotist's clinical decision-making

In addition to podiatrists, orthotists may also provide insoles to patients with diabetes. Podiatrists and orthotists have distinct vocational training, meaning that they differ regarding diagnostic procedures, construction of orthoses and therapeutic approach. Although each discipline has a specific focus on particular foot problems, both provide foot orthoses and shoes to treat foot impairments associated with elevated plantar forefoot peak pressures (Guldemond *et al.*, 2005). This anatomical region is of key importance as it is the most common area where high peak pressures occur (Lee *et al.*, 2014). These

high peak pressures produce painful inflammation in the capsule of the metatarsophalangeal joints and are one of the most common reasons for consultation in female patients (Naraghi *et al.*, 2014). However, patients with neuropathy cannot feel the pain produced by metatarsalgia, resulting in maintained high peak pressures under the metatarsal heads, a key risk factor for ulceration (Paton *et al.*, 2012).

The insole manufacturing process is subjective, studies have shown that there was almost no agreement between thirty foot experts on the location of high-pressure zones in three patients with metatarsalgia, not even between those of the same discipline (Guldemond *et al.*, 2005, Guldemond *et al.*, 2007). Furthermore, the design of the insoles made by thirty-one different foot experts for three patients with similar forefoot complaints varied greatly (Guldemond *et al.*, 2006, Stolwijk *et al.*, 2011). Although insoles are frequently used to reduce the plantar pressure under painful areas of the foot, there is still no consensus about the best way to manage high-risk patient's complaints with insoles (Stolwijk *et al.*, 2011).

2.1.3 Role of technology in clinical practice

In recent years there has been an exponential increase in the growth in the use of mobile devices and technology (Street *et al.*, 2014). Along with this technology growth, mobile phone and tablet applications (apps) for self-control health and management have flourished. There is some evidence suggesting that information aimed at helping patients to understand their health risks has increased adherence to their treatment, as well as improved their communication and trust with their practitioner (Adams, 2010). However, providing customised information for each patient can be perceived as costly and time-consuming. Nevertheless, the increasing availability of low-cost mobile phones and tablets could overcome this problem. These devices can be used as a new communication channel with the patient, to provide them with relevant and tailored educational information to check progress and outcomes of treatment. It can also enable the patients to access healthcare information and recommendations for their specific condition and enable contact with their practitioner in case of need.

Technology that supports clinical decisions improve diagnostic and patient safety. Moreover, the availability of technology for health care professionals has grown in line with the increased prevalence of apps and smart mobile devices (Patel *et al.*, 2015).

However, proven clinical effectiveness and patient safety do not seem to be sufficient to ensure adoption and implementation of new clinical technologies (Llewellyn *et al.*, 2014). Introducing these new technologies initially raises providers' costs as this requires training, interferes with the clinic workflow and patient management, and may result in a reduction in the number of patients seen in the short term (Jimbo *et al.*, 2013, Llewellyn *et al.*, 2014, Seifert *et al.*, 2016, Turner, 2016). Given that the current funding regime for providers is based on payment by results and rewards activity, it is not surprising that providers often see new technologies as risky.

Llewellyn *et al.* (2014) studied organisational and policy context for the adoption and implementation of clinical technologies. To this end, they performed a series of interviews and surveys of clinical staff, clinicians, managers and commissioners. They reported that providers could be one of the major obstacles to the adoption of new technologies. They also found that NHS providers did not perceive any central 'push' from the Department of Health or NICE to adopt or implement new clinical technologies. Moreover, negotiations over funding between providers and commissioners also delayed the implementation of these technologies. Finally, they found that clinicians without training or previous experience with technology did not understand its clinical need and utility.

In another study, Seifert *et al.* (2016) investigated the use of mobile device apps by occupational therapists during their clinical practice. They found that more than half of the participants did not use apps in therapy, with "not having access to the technology at work" being the primary reason. The main outcomes clinicians sought using apps was to promote skill building, support the therapeutic process and accurate feedback. Apps were mainly selected based on peer recommendations. The authors concluded that more therapists might use this type of technology if potential barriers were reduced or eliminated, such as the availability of technology, improved therapist training, allowing therapist input into app development and an enhanced evidence base.

Patel *et al.* (2015) studied the use of mobile device apps by junior doctors in their clinical practice. They found that junior doctors preferred using desktop-based computers because they found it challenging to read information on a small screen. Moreover, young clinicians with no previous experience of mobile device use in their clinical practice found

it difficult to integrate these into their normal workflow. Interestingly, participants preferred using mobile devices as a learning resource in their own time rather than as a tool exclusively for the workplace. Finally, some of the junior doctors felt that the use of these technologies in front of the patient or other senior colleagues could be perceived as being unprofessional. In contrast to this belief, patients reported positive perceptions toward their clinician using mobile device apps during their consultations.

New technologies can also help patients to better understand their conditions, which can increase their treatment adherence. Patient education for those people with diabetes has been proven to enhance self-management and engagement in their treatment (Tricco *et al.*, 2012). However, many patients with type 2 diabetes do not have access to this education or do not participate in self-management support programmes. This issue could be resolved through technology, as tele-education has the potential to improve accessibility and efficiency of care. Odnoletkova *et al.* (2016) explored the perceptions of patients, nurses and general practitioners regarding tele-coaching for those people with type 2 diabetes. To this end, 5 monthly telephone sessions of +/- 30 min were offered to 287 people with type 2 diabetes. The authors reported that 97.5% of patients available for a follow-up analysis declared that they were satisfied. They concluded that nurse-led tele-coaching of participants with type 2 diabetes was readily accepted by patients and providers.

There are studies investigating the actual practicality and patients' use of this type of technology (Hsu *et al.*, 2005, Strayer *et al.*, 2010, Sun *et al.*, 2011, Ashurst *et al.*, 2014, Ahern *et al.*, 2016, Spat *et al.*, 2016). Ashurst *et al.* (2014) conducted a study to design an app to help enhance the engagement of young patients with diabetes, regarding their appointments and management. This study had two different phases: in the first phase, 6 different teams of developers (with at least one British person aged 16 – 25 with type 1 diabetes) were asked to create an app. In the second phase, 56 patients, aged 16 – 25, with diabetes were asked to examine and try the 6 apps, choose one and use it in preparation for their upcoming clinic appointment. After the appointment, participants were asked to complete a questionnaire and add comments in a web-based forum. The authors concluded that apps are useful to engage young patients with their appointments. Moreover, they strongly suggested that young patients with diabetes should be asked for advice on the design process of apps.

One of the challenges of implementing technology in clinical practice is older people's lack of knowledge and experience. They tend to find such technology alien to them and do not feel compelled to try it and engage with it. However, Ahern *et al.* (2016) recruited patients aged 32 – 71 who had very different experiences with technology, ranging from those who were very experienced to others not normally using technological devices. They were suffering from chronic obstructive pulmonary disease and were asked to test and give feedback regarding an app designed to support the assessment and management of their condition. They concluded that patients benefited from the portability and flexibility of the tablet device in the examination room, despite their technology knowledge. Furthermore, Spat *et al.* (2016) tested the prototype of a mobile, tablet-based client-server system for treatment decisions and workflow support (GlucoTab®). This system was designed to support clinicians administering insulin therapy. The authors found a significant reduction in hypoglycaemia when using a computerised system for workflow and treatment decision support, compared to a paper-based process. Healthcare professionals accepted that the system was effective and patients adhered to its insulin dose suggestions. This supports earlier work that demonstrated that doctors found examination room computers a positive addition during assessment and management of patients (Hsu *et al.*, 2005).

Aligned with this idea, Strayer *et al.* (2010) explored the possible difference in patient's attitudes towards the use of new tablets and mobile devices during their clinical appointments. They interviewed patients immediately following a visit to a clinician and asked about their attitudes toward the technology used during the appointment. Results showed mostly positive patient perceptions of the tablets regardless of age, gender, race, ethnicity and income. However, some patients reported that they had experienced a depersonalisation during the appointment. This lack of interaction was also found by Street *et al.* (2014) when practitioners used computers during the consultation. They concluded that clinicians multitask during the appointments, having to interact with both patients and the computer to retrieve data, gather information and create treatment plans.

The different technological approaches have been explored in order to assist consultation. However, these approaches assist general consultation rather than to measure treatment outcomes. An example of this is the prevention of diabetic foot ulceration, through the use of insoles in order to achieve the greatest offloading possible.

However, Guldemond *et al.* (2006) showed that the clinical process for the identification of elevated plantar pressure performed by professionals appears to be insufficient. Plantar pressure devices are too time-consuming to set up and use, and the results they provide are too complex to interpret and use within the consultation. They also concluded that there is a lack of clinical devices that are user-friendly and focused on improving patient's outcomes.

Aspects of the physical examination, clinical reasoning and techniques for elevated plantar pressure screening have to be re-evaluated to improve this clinical process. Quantitative plantar pressure measurement is a valuable addition to screening. Although the cost of this equipment has decreased and easy-to-use software and hardware has become available, plantar pressure measurement is not standard in foot-care practices. There is also no prescription tool that helps podiatrists integrate data obtained from clinical assessment into their footwear and insole prescription. Furthermore, there is no technological solution capable of pre-calculating the expected pressure distribution on the plantar aspect of the foot. Therefore, and due to its serious implications, a technology-based solution is needed for day-to-day clinical practice. Nonetheless, before this solution can be achieved, it is necessary to fully understand the professionals' diagnosis and prescription process in order to design software to fulfil their needs. Further knowledge of the problems that practitioners face in their day-to-day practice would inform what is required in order to enhance treatment.

For this reason, I carried out research which aimed to investigate the factors that influence practitioner clinical decision-making. This was approached with qualitative research methods and the three primary objectives were:

1. To gain insight into the practitioners' aims when providing foot orthoses in relation to foot geometry, motion control, pressure redistribution, accommodation of deformity, as well as their perception of the patient's clinical needs (usability, outcome)
2. To identify what factors influence the assessment of patients and the specific design of the orthoses

3. To gain insight into how the aims of the prescription and the associated factors might then be prioritised and enhanced with the use of technological advancements.

Before this aim and objectives can be achieved, a full exploration and critical evaluation of the research published in relation to the biomechanics of the ulcerated diabetic foot and insole design needed to be carried out. This is presented in the following chapter, which then leads to the qualitative investigation in Chapter 4.

3 Literature review - Section 2: The biomechanics of foot ulceration and insole design for people with diabetes

A diabetic foot ulcer (DFU) is defined as "any necrosis, gangrene, or full-thickness skin defect occurring distal to the ankle in a diabetic patient" (Schaper *et al.*, 2012). This complication entails serious consequences to the patient, such as reduction in the quality of life, amputation, and in severe cases, death. In the previous section, a detailed literature review was presented about clinical decision making and management of this complication. However, a better knowledge of its pathogenesis and risk factors is needed to understand if this management provided by professionals is optimum and how it may be enhanced. Therefore, this section will provide a detailed and critical evaluation of the literature published about diabetic foot syndrome, its risk factors and different treatments.

3.1 Aetiology of ulceration in diabetes

Ulceration in diabetic foot occurs when a combination of risk factors, mainly peripheral neuropathy and high plantar pressures, present at the same time (Guiotto *et al.*, 2013). Foot deformity and peripheral vascular disease are also important risk factors that can trigger ulcer formation (Lepantalo *et al.*, 2011). Neuropathy in patients with diabetes has three aspects: sensory, motor and autonomic. Sensory neuropathy produces a loss of sensitivity that hinders the identification of traumas in the foot. Motor neuropathy leads to muscle degeneration, limited joint mobility and altered biomechanics of the foot, producing deformities that lead to imbalanced and increased pressures (Guiotto *et al.*, 2013). Autonomic neuropathy results in diminished sweating that makes the skin dry and more likely to crack. It also leads to callus formation which produces an increase in plantar pressures (Alavi *et al.*, 2014).

Due to neuropathic complications, the diabetic foot is not able to properly distribute high plantar pressures, leading to the maintenance of high pressures during walking, damaging the already altered soft tissue and subsequently leading to skin breakdown. This is compounded by peripheral vascular disease and an impaired immune

response in patients with diabetes, which hinders wound healing leading to increased risk of ulceration, predisposing the foot to complications and infection (see Figure 3.1).

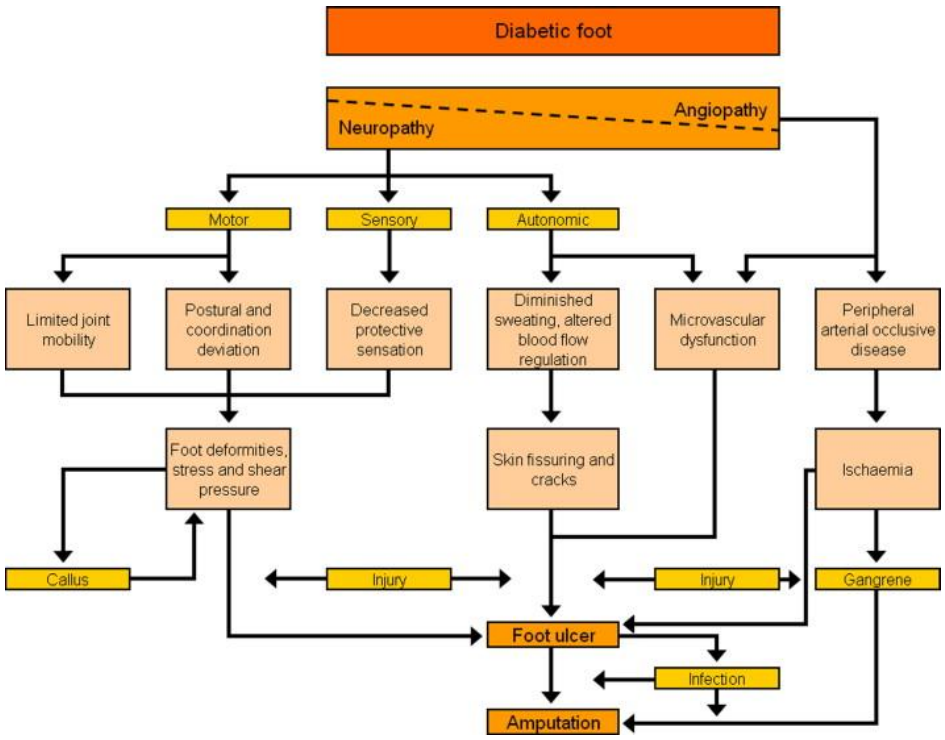

Figure 3.1: Pathway to ulceration adapted from (Lepantalo *et al.*, 2011)

3.2 Epidemiology of foot ulceration in diabetes

A patient suffering from DF syndrome will not develop and ulcer spontaneously, there is a combination of factors which will ultimately result in skin breakdown and ulceration. Therefore, it is of fundamental importance to identify the main risk factors leading to ulceration.

3.2.1 Risk factors for foot ulceration in diabetes

DFU are produced when two or more risk factors are present at the same time. The two main most common risk factors identified are peripheral neuropathy and abnormally high plantar pressures (Lepantalo *et al.*, 2011). The presence of peripheral vascular disease and deformity are also risk factors for ulcer formation (Boulton, 2010, Malhotra *et al.*, 2012, Fernando *et al.*, 2013). Moreover, people with diabetes have an impaired immune response, with a reduced ability to recruit inflammatory cells to the

damaged tissues, delaying wound healing and increasing the risk of infection (Leung, 2007). Other complications contributing to ulceration include poor vision, limited joint mobility and cardiovascular and cerebrovascular disease (Jeffcoate&Harding, 2003, Boulton, 2010, Turns, 2013). A higher risk of ulceration has also been observed among males and individuals within the inadequate glycemic control (Bortoletto *et al.*, 2014). The American Diabetes Association (ADA) published a consensus for the main risk factors for ulceration and amputation in (ADA, 2013) (Table 3.1):

Previous amputation	Past foot ulcer history
Peripheral neuropathy	Foot deformity
Peripheral arterial disease	Visual impairment
Diabetic nephropathy	Poor glycemic control
Cigarette smoking	

Table 3.1: Risk factors for ulceration and amputation

Hoffman *et al*. (2015) focussed on the health risks associated with smoking cigarettes; people with diabetes who smoke are at a higher risk of cardiovascular disease, premature death and increased rate of microvascular complications (ADA, 2013). Cessation of smoking was related to an improvement of the individual's glycaemic control and reduced blood pressure in newly diagnosed type 2 diabetic patients. Interestingly, a reduction in the prevalence of both peripheral vascular disease and peripheral neuropathy (two of the main risk factors for ulcer formation) was shown in patients with diabetes that stopped smoking (Voulgari *et al.*, 2011). This supports the hypothesis that smoking has an adverse influence on the glycaemic control, contributing to the final precipitation of ulceration risk factors.

Diabetes is defined by high levels of blood glucose (hyperglycaemia), the control of which is fundamental to the management of diabetes. There is evidence of decreased rates of microvascular and neuropathic complications in patients with improved glycemic control (UKPDS, 1998a, UKPDS, 1998b), which are two of the main risk factors for ulcer formation. It has also been shown that glycaemic control decreases the risk of cardiovascular disease, lowering the mortality rate of diabetics due to coronary

complications (ADA, 2013). Lack of physical activity, combined with obesity, also increases the risk of developing DF (Lima *et al.*, 2014). The most prevalent socio-demographical risk factor is a sedentary lifestyle, followed by being overweight, which is normally as a result of the lack of exercise. Regular exercise has been shown to improve blood glucose control, reduce cardiovascular risk factors, contribute to weight loss as well as improve well-being. Furthermore, regular exercise may prevent type 2 diabetes in high-risk individuals (ADA, 2013).

3.2.2 Neuropathy

Peripheral neuropathy represents the main risk factor for DF ulcers and may be sensory, autonomic or motor. Sensory neuropathy decreases or eliminates the protective sensation of the foot (Sriyani *et al.*, 2013) so that individuals are unable to sense either repetitive or isolated trauma which may occur during walking or other activities, leading to skin damage. Motor neuropathy is associated with hyperextension of the metatarsophalangeal joints, clawing of the toes and distal migration of the fibro-fatty pad on the plantar aspect of the forefoot (Abouaesha *et al.*, 2001). This process subsequently leads to increased forefoot pressures, one of the main risk factors for ulceration in the presence of neuropathy (Abouaesha *et al.*, 2004). Autonomic neuropathy produces a decrease in sweating that can lead to skin breaks by dryness itself. Dehydrated skin loses its elastic mechanisms and therefore, its ability to adapt to feet movement, tending to crack easily. It also leads to callus build up under areas of increased pressure, which in turn, further increases plantar pressures (Abouaesha *et al.*, 2001). Furthermore, neuropathy has a major influence on plantar pressure changes and behaviour. Ledoux (2013) found aberrant plantar pressure patterns in 7% of healthy subjects, 17% of the diabetic feet, 31% of the diabetic feet with neuropathy and 100% of the diabetic feet with a history of ulcers.

3.2.3 Plantar pressure as a risk factor

The development of a DF ulcer is a multi-factorial process which is primarily associated with neuropathy and high plantar pressures. Peak plantar pressure (PP) is typically defined as the highest localised pressure under the foot. Elevated peak plantar pressure has been shown to be a contributing factor to skin breakdown, especially when repeated at a specific area in patients with peripheral neuropathy (Abouaesha *et al.*, 2001,

Patry *et al.*, 2013). As explained above, increased peak pressure may result from a range of factors and complications derived from DM, such as deformities, plantar hyperkeratosis, lack of joint movement, tissue stiffness or history of previous ulcers or amputations (Waldecker, 2012, Healy *et al.*, 2013). People with DM have higher peak pressures than healthy subjects (Patry *et al.*, 2013). Moreover, these pressures are greater on the forefoot in patients with neuropathy when compared to non-diabetics without this condition (Ledoux *et al.*, 2013, Patry *et al.*, 2013). There are some factors that influence ulcer formation such as soft tissue characteristics, joint mobility and biomechanics (Payne *et al.*, 2001, Barn *et al.*, 2015). However, they also have a significant influence on plantar pressures. Moreover, if these factors influence both ulcer formation and plantar pressures, they are key risk factors in the whole process.

3.3 Factors that influence pressure

Plantar pressure is one of the main risk factors for diabetic foot ulceration (Patry *et al.*, 2013), so it is important to gain a thorough insight and understanding of the different factors that may influence plantar pressures during walking. Diabetic neuropathy has been shown to produce several conditions on the foot, such as decreased joint mobility, altered muscle function and tissue stiffness. If these conditions are present at the same time, they result in foot deformities and alterations of foot motion that will also affect plantar pressures and balance. Given that plantar pressure is one of the key risk factors for ulceration, it is important to understand the factors which can influence differences in pressure between individuals.

3.3.1 Soft tissue influence on plantar pressures

Soft tissue on the plantar aspect of the foot has two layers, consisting of fatty and connective tissues. These function to absorb shock loading on the foot, particularly on the forefoot and heel regions (Ozdemir *et al.*, 2004, Natali *et al.*, 2010). The flexibility provided by collagen fibres can be altered by both repetitive trauma and diabetes (Cavanagh *et al.*, 1993, Hsu *et al.*, 2007, Hsu *et al.*, 2009). Patients with diabetes and neuropathy present stiffer plantar tissues than healthy subjects (Sun *et al.*, 2011) and this increase in stiffness leads to a decrease in its capacity for shock absorption (Crawford *et al.*, 2007, Pai&Ledoux, 2012). Furthermore, repetitive loading while walking leads to a

local thickening of the epidermis due to accelerated keratinization (callus formation) in the epidermis (Wang&Sanders, 2003, Kim *et al.*, 2010). Subsequent callus formation allows the skin to better resist repetitive traumas; however, it also increases the peak pressures on its location (Zhang, 2006).

There is evidence of a stiffer soft tissue under the metatarsal heads in people with diabetes (Sun *et al.*, 2011), meaning that the tissue less able to distribute pressure via deformation (Gefen, 2003). There is also a strong inverse relationship between plantar tissue thickness and dynamic foot pressures (Zheng *et al.*, 2000, Abouaesha *et al.*, 2001, Klaesner *et al.*, 2002). Not surprisingly, tissue stiffening has been found to significantly increase plantar pressure, thereby, becoming an additional predictive factor of ulcer development (Abouaesha *et al.*, 2001, Sun *et al.*, 2011, Periyasamy *et al.*, 2012, Patry *et al.*, 2013).

3.3.2 The influence of foot deformity and biomechanics on plantar pressures

Foot shape and foot biomechanics influence plantar pressure, especially under the metatarsal heads. Plantar pressures are highest at the metatarsal heads during the push-off phase of walking (80% of stance) as, at this point, weight bearing and push-off forces are greatest and the weight-bearing contact area is smallest (Kelly *et al.*, 2000). Metatarsal head plantar pressures are typically higher in people with DM and peripheral neuropathy (Mueller *et al.*, 2003). Also, soft tissues under the metatarsal heads tend to be thinner and stiffer in subjects with DM and peripheral neuropathy compared with healthy subjects (Periyasamy *et al.*, 2012, Patry *et al.*, 2013). These mechanical effects, directly as a consequence of DM and peripheral neuropathy, contribute to excessively high plantar pressures, which are not sensed by the individual and subsequently, lead to skin breakdown (Mueller *et al.*, 2006).

Foot morphology can play a role in determining the biomechanical behaviour and function of the foot (Guiotto *et al.*, 2013). Diabetes and more specifically, diabetic neuropathy, has been shown to result in decreased joint mobility (Garcia-Alvarez *et al.*, 2013). Limited joint mobility plays a key role in the abnormal biomechanics of the foot and ankle in the diabetic patient (Mueller *et al.*, 1989, Zimny *et al.*, 2004). Structural

changes occur within the tendon and capsule of the diabetic patient, leading to decreased elasticity and tensile strength, which subsequently results in instability at joints causing subluxations or overall stiffness of the foot. In both cases, the result is poor foot biomechanics (Kim, 2013). It has also been widely demonstrated that people with diabetes are characterised by excessive ankle rigidity (Guiotto *et al.*, 2013). Zimny *et al.* (2004) studied the relationship of joint mobility with plantar pressures in a cross-sectional study of 70 patients with diabetes and 30 healthy control subjects. They concluded that the ankle joint and first metatarsophalangeal joint (MPJ) mobility showed a strong inverse correlation with the pressure time integral of the forefoot. Moreover, joint mobility reduction of the ankle and first MPJ resulted in an elevated time-dependent load of the forefoot. This suggests that foot morphology affects plantar pressure and plantar pressure is related to ulceration, therefore, foot morphology is related to ulceration (Guiotto *et al.*, 2013, Ledoux *et al.*, 2013, Fernando *et al.*, 2014).

The relationship between foot type, foot deformity and ulceration has been previously explored (Ledoux *et al.*, 2005). Pronation of the foot is linked to neuropathy and is more prevalent in people who have a longer duration of diabetes (Formosa *et al.*, 2013). Those patients who exhibit excessive foot pronation also have limited joint mobility of the first MPJ. The limited joint mobility of the foot has a prevalence of 8% to 58% in diabetes and may indicate risk of developing pronation. This pronation may, in turn, lead to other foot deformities, such as hammertoes or *hallux valgus* and altered foot mechanics (Pecoraro *et al.*, 1990, Robertson *et al.*, 2002, van Schie *et al.*, 2004, Crawford *et al.*, 2007, Allan *et al.*, 2015, Bus, 2015) which produce increased pressures (Murray *et al.*, 1996, Reiber *et al.*, 1999). The metatarsal heads are a common site of foot ulceration and it has been shown that toe extension produces a significant increase in stiffness on the plantar soft tissues, which increased plantar pressures during the push-off phase of gait (Garcia *et al.*, 2008). In support of this idea, recent foot models showed that soft tissue stiffness under the metatarsal heads is modified depending on the MPJ angle. Accordingly, soft tissues under metatarsal heads (MTH) exhibited in stiffness of up to 20% in joint extension compared to neutral positions (Chen *et al.*, 2003). Foot deformities and altered biomechanics have a direct influence on plantar pressures, and therefore on ulcer formation.

Peripheral neuropathy has a considerable effect on the biomechanics of the foot in people with diabetes (Pham *et al.*, 2000). Human gait is a complex movement composed of a series of phases. The proprioceptive system informs the position and movement of the foot, providing it with a mechanical protection function that will detect any potentially dangerous movement or position while walking (Yu *et al.*, 2011). The foot makes small adjustments during gait which depend on sensory feedback to avoid prolonged pressure to any one localised area (Kim, 2013). However, in the case of the diabetic foot, feedback from the proprioceptive system is poor (Yu *et al.*, 2011), which leads to a delay, or complete absence, of these small adjustments. Some studies have found pressure patterns to be influenced by spatial-temporal gait variables including walking speed, cadence, and step length, as well as morphological characteristics such as height and bodyweight (Fernando *et al.*, 1991, Cavanagh *et al.*, 1997, Morag&Cavanagh, 1999, Cavanagh *et al.*, 2000, Mueller *et al.*, 2003, Menz&Morris, 2006, Martinez-Nova *et al.*, 2008). Limited joint mobility, produced by peripheral neuropathy, contributes to increased plantar pressures by limiting foot flexibility and restraining the forward progression of body weight during the stance phase of gait (Fernando *et al.*, 1991, Fernando *et al.*, 2013). An increase in unsteadiness has also been observed in patients with DM, most likely due to a thickening of the Achilles tendon and plantar fascia that is associated with a more rigid foot less adaptable to walking on different surfaces (Garcia-Alvarez *et al.*, 2013, Allan *et al.*, 2015). Altered perception of the foot and lack of joint movement alter normal gait, leading to increased pressures and risk of ulceration.

Motion and gait patterns are different between healthy subjects and those with diabetes, especially if they have neuropathy. Fernando *et al.* (2013) found that patients with neuropathy walked slower and had a reduced stride length when compared to diabetic patients and healthy subjects. They also found that people with neuropathy spent a longer period of time in the stance phase compared to subjects with DM. They demonstrated a reduced range of movement in patients with neuropathy when compared to healthy subjects, except for hip flexion. Therefore, it is probable that elevated plantar pressure, coupled with a longer period of time spent in stance in neuropathic patients, contributes to the susceptibility to skin damage through prolonged mechanical load on tissue, leading to skin breakdown and ulceration (Fernando *et al.*, 2013).

Since foot structure can affect peak pressure (Ledoux *et al.*, 2005, Guiotto *et al.*, 2013) and peak pressure can predict ulceration, it is possible that ulceration may be predicted by foot structure. In line with this, foot deformities, such as hammer/claw toe deformity or hallux limitus, have been associated with an increased risk of ulceration (Ledoux *et al.*, 2005, Cowley *et al.*, 2008). Guiotto *et al.* (2013) found a close relationship between foot morphological alterations and plantar ulcerations. This is in agreement with (Ledoux *et al.*, 2005), who demonstrated that foot structure was one of the main factors which could explain differences in peak pressure. Moreover, there is a direct relationship between diabetes and changes in foot morphology, especially in the presence of neuropathy, due to its effect on muscles and tendons (Kim, 2013). A cavus foot was found to be frequent among patients with diabetes, and higher pressures were found when compared to non-diabetic feet (Ledoux *et al.*, 2005). Therefore, there is evidence that foot morphology has the potential to impact on peak plantar pressures, which can ultimately mean that it may have an influence on ulcer development.

Variability in PP in patients with diabetes is significantly related to the presence of neuropathy (Payne *et al.*, 2001). This condition entails important complications such as increased soft tissue stiffness, reduced range of movement on the key joints of the foot and deformities due to muscle and ligament weakness. A small concurrence of these complications can be significant predictors of dynamic function (Payne *et al.*, 2001). These factors are insufficient on their own but combined they will ultimately result in the formation of a diabetic foot ulcer (Reiber *et al.*, 1999). Moreover, it is likely that some of these complications are present at the same time, given their high prevalence (over 40% for all of them) amongst people with diabetes (Chao *et al.*, 2011, Allan *et al.*, 2015).

3.3.3 Plantar pressure thresholds for ulceration

There have been attempts to establish a pressure threshold above which ulceration is more likely to happen. However, there are reports of different thresholds for ulcer development, ranging from 300 to 1100 KPa (Waldecker, 2012). Armstrong *et al.* (1998b) recruited 219 patients with diabetes in a case-control study to set an ulceration risk threshold; cases were patients with a recent history of ulceration and the controls comprised patients without a history of ulceration. Barefoot plantar pressures were collected with a novel Emed platform and they found higher pressures on the forefoot in

patients with a history of ulceration. They set the threshold for ulceration at 700 KPa, but the sensitivity and specificity were not high enough, leading them to conclude that there is no threshold, but that higher peak pressures lead to increased risk.

Frykberg *et al*. (1998) studied a cross-sectional group of 251 patients of different ethnicities aiming to determine the risk of ulceration associated with high foot pressures and peripheral neuropathy in a large and diverse diabetic population. They collected barefoot pressure data in their group of 251 patients with diabetes and neuropathy using an F-scan mat system. They also performed neuropathy screening tests and tested joint mobility. Using a logistic regression between the different screening variables and pressure, they concluded that both high foot pressures and neuropathy are independently associated with ulceration, and this led them to suggest a threshold of 588 KPa.

Owings *et al*. (2009) performed a cohort study and recruited subjects with diabetes and neuropathy from a database of 2625 eligible patients created over a period of 18 years. They identified 190 surviving patients with prior plantar ulcers of the forefoot and 49 patients agreed to participate. All participants had had a yearly follow up appointment for at least five years and had remained healed at least for over 90 days. Barefoot and in-shoe plantar pressures were collected with Novel® devices. They concluded that barefoot peak pressure is a poor predictor of peak in-shoe pressure and that in-shoe pressure is a key variable that should be investigated for foot ulcer risk in diabetic patients. They reported a mean barefoot peak plantar pressure of 556 KPa but large inter-subject variability (107 – 1,192 KPa) and a considerably lower mean in-shoe peak plantar pressure of 207 KPa. They could not establish a threshold for ulceration and recommended to provisionally adopt 200 KPa as previously suggested by Guldemond (2007).

As yet, a peak pressure threshold for ulceration risk has not been definitively established (). The difficulty in establishing a PP threshold is mainly because DFU is a multifactorial process affected by direct vertical pressure but also by shear stress (Patry *et al.*, 2013). Moreover, DFU is also influenced by other factors such as peripheral vascular disease, glycemic levels or activity and lifestyle (Patry *et al.*, 2013, Fawzy *et al.*, 2014). As detailed previously, there are several factors that can influence plantar pressures. However, PP is only one factor in a multifaceted pathway to diabetic foot ulcer

formation, and, importantly, it has been shown that ulceration can occur in presence of normal PP (Armstrong *et al.*, 1998a).

Other factors which have been linked to ulceration include peripheral neuropathy, peripheral vascular disease, glycaemic levels, socio-economical background or activity level (Noor *et al.*, 2015). The glycaemic state and the lifestyle of patients with diabetes depend on the self-management and can often be difficult to change because of poor compliance with lifestyle advice change (Abubakari *et al.*, 2016). This low adherence to healthier lifestyles will result in increased risk factors for foot ulceration and other complications from DM such as retinopathy or nephropathy. Since many of these factors, such as neuropathy, are out of the direct control of the clinician, most conservative treatment approaches include reducing PP during walking and educating the patient regarding foot care to prevent ulceration (Stacpoole-Shea *et al.*, 1999).

Although many threshold values have been suggested for risk of ulceration, the only certainty for ulceration is that the risk increases as peak pressure increases. Another factor to consider are the large variations in systems and ways of measuring and recording PP, which make it difficult to arrive at a consensus regarding the best system and the best way of obtaining a sensible and reproducible measurement (Armstrong *et al.*, 1998b). However, Guldemond *et al*. (2007) found that if peak pressures were lower than 200 KPa, ulceration did not occur. Therefore, this peak pressure could be set as a "safe" threshold for ulcer prevention until a more accurate ulceration threshold is determined. Importantly, previous studies have shown that in-shoe pressures can be reduced to the 200 KPa range with appropriately designed prescription footwear interventions (Owings *et al.*, 2009).

3.4 Plantar pressure measurement methods

3.4.1 Devices

There are two main devices used to collect plantar pressures: platforms (used for barefoot collection) and in-shoe pressure devices. Although pressures can be measured under either static or dynamic conditions, dynamic pressure measurement appears to be more sensitive and reliable for identifying at-risk feet (Patry *et al.*, 2013). In-shoe devices are clearly advantageous over platforms as they allow in-shoe pressures to be investigated which are known to differ considerably from barefoot pressures (Chevalier *et al.*, 2010).

Also, barefoot peak pressure is a poor predictor of peak in-shoe pressure. Therefore, the in-shoe pressure is a key variable that should be examined for foot ulceration risk in diabetic patients (Owings *et al.*, 2009). Accordingly, these in-shoe plantar pressure devices have been used over the last three decades to monitor the interaction between the foot and the shoe or insole, during either static or dynamic activities (de Castro *et al.*, 2014).

Accurate measurement and assessment of plantar pressures are important to detect changes in pressure, which may be small, but still meaningful (de Castro *et al.*, 2014). Also, in order to be able to assess individuals, the device used needs to be reliable (Atkinson&Nevill, 1998). Reliability can be defined as the consistency of measurements or the absence of measurement error (Jackson, 1990). In practice, some amount of error is always present with continuous measurements due to noise and human movement variability. Therefore, reliability could be considered as the amount of measurement error that has been estimated that does not bias the result (Atkinson&Nevill, 1998).

The insole of the in-shoe plantar pressure device is composed of an array of sensors that quantify the pressure. These sensors are arranged in rows and columns (Cavanagh P. R., 1992) and enable monitoring of the entire plantar area of the foot during walking. These sensor insoles can be connected by cable to an electronic box, which sends the data to a computer via Bluetooth® telemetry. The insoles are made of a capacitive sensor with elasticity to conform well to the three-dimensional surface of the orthotics. These sensors are formed from two conductive electrically charged plates separated by a dielectric elastic layer when pressure is applied to the sensor, the dielectric elastic layer bends decreasing the distance between the two plates, producing a voltage change proportional to the pressure applied (Figure 3.2).

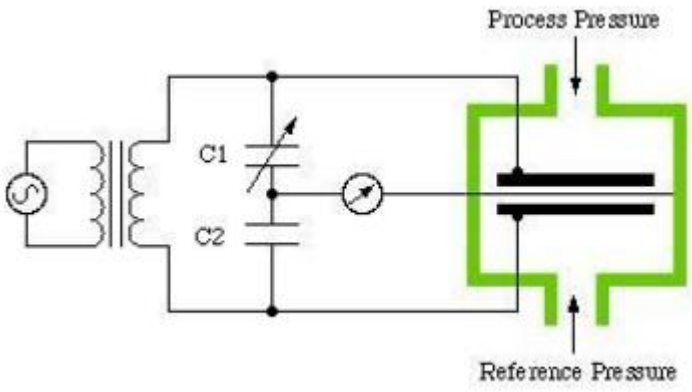

Figure 3.2: Capacitive sensor adapted from (Razak et al., 2012)

3.4.2 Plantar pressure analysis and pressure outcome measures

The first step when processing a continuous in-shoe plantar pressure measurement is to segment the data into different steps for each foot. A mask is then defined to divide the plantar aspect of the foot into different regions which are usually analysed separately. The most common masks regions are heel, midfoot, first metatarsal head, central metatarsal heads, fifth metatarsal head, hallux and toes. To define these regions, the corresponding sensors from the insole are identified and an appropriate mask defined (Figure 3.3). Once the masks are defined, different pressure calculations are performed to define a small number of outcomes which characterise plantar pressure behaviour. The outcome peak pressure is defined as the highest pressure in any sensor across a given mask (anatomical region) (Bus&Waaijman, 2013). In contrast, mean pressure is calculated as the average pressure across all the sensors in a given region. Finally, the pressure time integral is defined as the time integral of the mean pressure across all sensors in a particular region during one-foot step. This is calculated as the area under the mean pressure-time curve of a particular region (Waaijman&Bus, 2012).

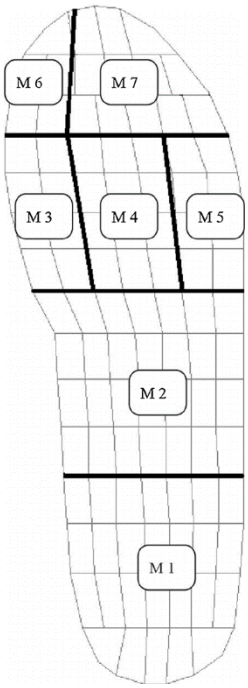

Figure 3.3: Pedar insole mask adapted from Bergstra *et al.* (2015)

Peak pressure and the pressure-time integral are the two most commonly used outcomes in studies investigating plantar pressure behaviour. There are several studies that show that these two outcomes are highly correlated. However, only peak pressure has been associated with ulceration in prospective studies (Frykberg *et al.*, 1998, Pham *et al.*, 2000), while the pressure-time integral has shown to influence ulceration only in retrospective studies (Stess *et al.*, 1997). Interestingly, some authors consider the pressure-time integral a more relevant parameter than peak pressure because it incorporates pressure as well as time factors, which have been suggested to be important in ulcer formation (Soames, 1985, Hsi *et al.*, 2002).

3.4.3 Reliability of in-shoe plantar pressure measurement

Reliable plantar pressure measurements are of key importance to assess the risk of ulceration. However, plantar pressure values vary from step to step and, even more, between separate days. There are many variables that may influence plantar pressure values, which are not only intrinsic to the subject but also dependent on the environment where the data collection is performed, or the device itself. Walking is variable, with no two steps the same (Putti *et al.*, 2007), feet muscles and joints move in a very complex

motion to adapt to the ground and maintain balance. Also, while collecting data, subjects are asked to walk in an unusual laboratory environment which may influence their pattern of walking. In addition, physical changes can happen in the subject, such as inflammation or pain, or psychological states between separate testing days. On the other hand, all data collection will have some noise within the data that is produced by the device itself. Given the importance of plantar pressure measurement, the potential for variability in each subject's walking pattern, devices that collect reliable data whilst minimising noise and errors are needed.

Reliability of in-shoe plantar pressures has been studied by several authors. Ramanathan *et al*. (2010) recruited 27 healthy male subjects and asked them to walk over a 26-metre walkway. They used off-the-shelf running shoes without insoles and repeated the measurement one week later. Peak pressures and pressure-time integral were determined and showed high repeatability on all the masks. In another study, Putti *et al*. (2007) recruited 53 healthy subjects and also used standard running shoes. A mean of 12 days passed from the first to the second data collection days. They also studied peak pressures and pressure time integral between other outcomes, obtaining good repeatability results. Another study by Godi *et al.* (2014) recruited 16 young healthy subjects, collecting data in two walking sessions, two days apart, wearing standard running shoes. They showed good repeatability for peak pressures across the whole foot. Finally, de Castro *et al.* (2014) recruited 40 young healthy participants and placed two in-shoe devices, one on top of each other, inside standard ballet sneakers. They showed good repeatability results for peak pressures and pressure time integral. However, this approach may not be the best choice, as systems can interfere and influence each other's measurement as they are in direct contact. Nonetheless, all studies came to the same conclusion that peak pressure and the pressure-time integral are reliable outcomes to report plantar pressures.

One of the most popular and reliable in-shoe devices used to collect plantar pressures is the Novel Pedar® system. This in-shoe pressure device has been tested by several authors in the literature, showing promising and relatively reliable results (Quesada *et al.*, 1997, Murphy *et al.*, 2005, Hurkmans *et al.*, 2006, Putti *et al.*, 2007, Gurney *et al.*, 2008, Chevalier *et al.*, 2010, Ramanathan *et al.*, 2010, Sawacha, 2013). It has been shown to have lower variance across sensors when compared to the F-scan

(Quesada *et al.*, 1997). All of the authors concluded that the Pedar system is reliable, but there is some controversy between some of the papers in the midfoot area. Murphy *et al*. (2005) concluded that the system can be used to measure contact area and plantar pressure beneath the midfoot, with excellent reliability in multiple trials of the same subject. On the other hand, Ramanathan *et al*. (2010) and Putti *et al.* (2007) were in agreement that the Pedar is a reliable system, but that the pressure-time integral data derived from the midfoot region is the least repeatable. Putti *et al.* (2007) also point out that no two footsteps in a ‘‘normal’’ subject are identical, and therefore, the repeatability achieved by the Pedar system is clinically acceptable.

In-shoe plantar pressure reliability has been studied by several authors using different approaches. Most of the studies conclude that peak pressure and the pressure-time integral are repeatable and reliable outcomes. Furthermore, the Pedar in-shoe system has shown to be the most repeatable device for plantar pressure collection. However, all previous studies have collected plantar pressure data from healthy subjects. This cohort may have gait and pressure patterns which are more consistent and potentially different from patients with diabetes and peripheral neuropathy. Moreover, all studies used standard shoes with flat insoles inside, rather than the customised insoles that are typically prescribed for pressure offloading. This gap in the literature was the basis for the first quantitative study presented in this thesis, which aimed to quantify the level of reproducibility of plantar pressure measurements in individuals with diabetes and neuropathy using fully customised insoles.

3.5 Footwear interventions for reducing pressure

Given the key role of elevated plantar pressure in DF ulceration, different interventions have been employed to reduce pressure. These strategies include various types of footwear, insoles, orthotics and offloading surgery among others (Bus *et al.*, 2004, Cavanagh&Bus, 2010, Healy *et al.*, 2013). Conservative methods are always preferable to surgical approaches, especially in high-risk populations. Therapeutic footwear and insoles have shown to be effective in pressure offloading (Luger *et al.*, 2001). Accordingly, they are normally prescribed to patients with diabetes in order to prevent ulcer formation. In the following sections, a brief literature review is presented

on both approaches so that the reader can gain a better understanding of their pros and cons.

The use of specially designed footwear is a common approach for reducing plantar pressures with the aim of preventing ulceration (Cavanagh *et al.*, 2000). The rocker shoe is the most commonly prescribed design (Schaff&Cavanagh, 1990) because it has been shown to be effective for offloading peak pressures (Uccioli *et al.*, 1997). The sole of these rocker shoes is curved which helps the foot move forward during the last phase of the step. This shoe prevents MPJ extension during the step, thereby reducing peak pressures under metatarsal heads (Hutchins *et al.*, 2009). There are two main types of rocker shoe which differ in sole shape, the traditional rocker and the curved rocker, with both types possessing a stiff sole to prevent it from bending (Figure 3.4). The contour of the traditional rocker has a sharp apex at approximately 55% of shoe length (Hutchins *et al.*, 2009) where rocking occurs. On the other hand, the curved rocker shoe has a more gradual curve on the apex of the shoe where this rocking movement happens more gradually.

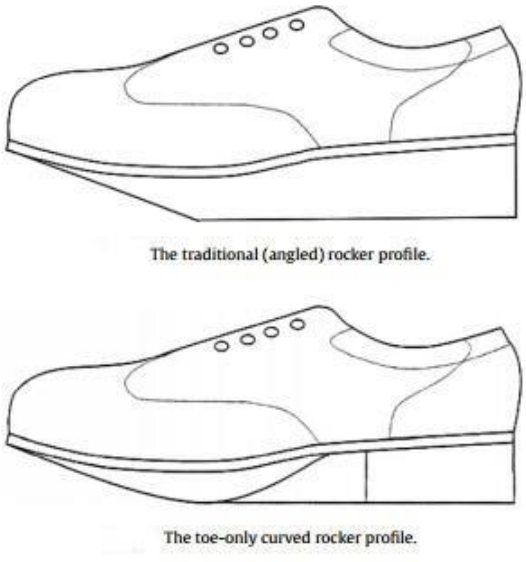

Figure 3.4: Types of rocker shoe adapted from (Hutchins et al., 2009)

Rocker shoes are commonly prescribed to patients with diabetes in order to offload pressures. The rocking motion of this type of shoe has shown to be effective reducing pressure when compared to normal oxford shoe (Healy et al., 2013). Moreover, there is evidence of pressure reduction on the central metatarsal heads with rocker shoes

(Waaijman *et al.*, 2012, Chapman *et al.*, 2013). However, there is some controversy in the efficacy of this type of shoe in ulcer prevention, for example, Uccioli *et al*. (1997) found evidence of ulceration rate reduction in patients using therapeutic footwear, whereas Reiber *et al.* (2002) did not find any reduction in the rate while using this type of shoe.

The main issue that this type of footwear presents is patient compliance (Williams *et al.*, 2007). Despite the beneficial properties of this shoe, it has been reported that patients want to have a choice in footwear according to their needs and are particularly focused on the appearance of the shoe. Therapeutic footwear may not meet those needs, instead, ending up in a cupboard (Williams *et al.*, 2007). Williams *et al*. (2007; 2010) found that therapeutic footwear replacing normal shoes reinforces the stigma of foot deformity and disability. Above all, in female patients, the therapeutic shoe will influence and restrict their choice in clothes, which may hinder their adherence to this prescription (Williams *et al.*, 2010). In modern society, external appearance is very important, especially for women, and the impact that this footwear has on appearance may lead to a negative emotional response in this group of patients (Williams *et al.*, 2010). Therefore, therapeutic footwear may not be the best solution for pressure offloading and other options that do not influence footwear choice need to be considered.

3.6 Insoles for reducing pressure

Insoles represent a viable alternative to footwear for reducing in-shoe plantar pressures and there are two main different types of insoles, off-the-shelf and custom-made.

3.6.1 Off-the-shelf insoles

Off-the-shelf insoles are mass produced standard insoles that are not specifically designed to fit the shape of the individual patient's foot. There are two types of off-the-shelf insoles, flat insoles and contoured insoles. Flat insoles consist of a layer of material with a varying thickness in the shape of the shoe and are normally made of cushioning materials, such as soft EVA. This type of insole can be bought from a high street shop and offers extra cushioning, over and above that provided by the sole of the shoe. Contoured off-the-shelf have a contoured shape to give support to the arch, and are made

to fit a generic foot shape, including a variety of arch heights. These insoles can be found in different materials of different densities, cushioning most frequently. They can also have other additions, such as wedges in order to try and mimic many of the physical characteristics of customised devices (Redmond *et al.*, 2009). While off-the-shelf all-purpose comfortable insoles may help to offer some cushioning, these are available in a limited number of shapes and materials and are hardly capable of fitting specific foot types and safety shoes (Caravaggi *et al.*, 2016).

3.6.2 Custom made insoles

Custom made insoles or total contact insoles are tailor made to fit the shape of the patient's foot, offering support across the whole plantar aspect of the foot. This type of insole is thought to accommodate deformities and relieve areas of excessive pressure by evenly distributing pressure over the entire plantar surface (Mueller *et al.*, 2006). Total contact insoles maximise the contact area with the foot and provide arch support in the midfoot region, which has been shown to help to unload the metatarsal and heel regions (Ibrahim *et al.*, 2013). These insoles are usually more expensive than off-the-shelf insoles since the design requires an in-depth examination with a podiatrist and additional measurements, but the user generally experiences a greater uniform pressure distribution, increased comfort, and less pain (Caravaggi *et al.*, 2016)

3.6.2.1 Casting technique

In order to fabricate custom-made foot orthoses, a negative model of the foot is used to create a positive plaster mould which can be modified and used as a template around which the foot orthoses are shaped. The classic casting technique is the non-weight bearing plaster of Paris, which is widely used and is considered by many to be the gold standard (McPoil *et al.*, 1989, Trotter&Pierrynowski, 2008). For this technique, the foot is held in neutral position by the caster. The degree of accuracy of the plantar geometry and the correct alignment of the foot is heavily influenced by the skill of the clinician and casting can be a time-consuming and difficult task (Trotter&Pierrynowski, 2008, Carroll *et al.*, 2011).

Furthermore, placing the foot in different alignment positions for casting will have implications for the plantar surface contours and the position that the resultant foot

orthoses will place the foot in (Chuter *et al.*, 2003). The semi-weight bearing posture with foam box is probably the most popular casting technique because it is quicker and cleaner than plaster (Carroll *et al.*, 2011). Recently, 3-dimensional (3D) surface scanners and digitizers, able to scan the foot directly have become available, meaning that accurate computer models of the foot shape can be generated (Guldemond *et al.*, 2006, Stajer *et al.*, 2011, Telfer *et al.*, 2012).

The casting technique is not the only factor which can influence cast quality, hence the functionality of the final orthosis; the final product can also be affected by the practitioner's ability and experience. There are several studies which have investigated the influence that the practitioner may have in the casting process. Interestingly, Chuter *et al.* (2003) did not find a statistically significant difference between the experienced and inexperienced clinicians. However, in another study, Trotter *et al*. (2008) found that foot care professionals are consistent with themselves (intra-caster) but, both methods show poor reliability between practitioners (inter-caster). Carroll *et al*. reported an increased measurement error in the forefoot to rearfoot alignment, both within and between the raters, when casting with the neutral suspension technique (Carroll *et al.*, 2011).

3.6.2.2 Manufacturing process

Once the cast is taken, there are two common approaches to manufacturing, traditional and CAD/CAM. For the traditional approach, the cast is filled with plaster to obtain a positive copy of the foot, which is then used to mould the insole. Following the prescription, the material for the shell of the insole is heated in an oven to make it malleable. It is then applied on top of the plantar aspect of the positive cast of the foot and introduced in a vacuum device to adapt the material to the shape of the cast. Once the first layer of material has cooled and is no longer malleable, more layers are applied on top of each other until the shape and height of the insole under the rear and mid foot is reached. The forefoot region (starting just proximal to the metatarsal heads) is flat, normally made with layers of cushioning materials to reduce PP. The insole is then finalised by glueing on a top and/or cover if required.

In the CAD/CAM manufacturing technique, the cast can also be filled in with plaster and this positive reproduction of the foot is scanned in a 3D scanner to obtain a 3D file. Another approach is to scan the foot of the patient rather than using a foam box

or plaster of Paris. This 3D file is then loaded into the insole design software, where a template of an insole is loaded and modified to replicate the plantar aspect of the foot. Then, the different additions are added and the file is sent to a milling station that will mill the insole out of a block of material.

3.6.3 Customised insoles for reducing pressures

There are many studies supporting the idea that the effectiveness of custom-made insoles is superior to that of off-the-shelf insoles (Postema *et al.*, 1998, Bus *et al.*, 2004, Mueller *et al.*, 2006, Owings *et al.*, 2008, Redmond *et al.*, 2009, Paton *et al.*, 2012, Ibrahim *et al.*, 2013). For example, Ibrahim *et al.* (2013) found a significant reduction in the mean plantar pressures under the metatarsal heads with total contact insoles. This pressure reduction under the metatarsal heads, when using customised insoles, has also been found by other authors (Lord&Hosein, 1994, Brown *et al.*, 1996, Kato *et al.*, 1996, Postema *et al.*, 1998, Bus *et al.*, 2004, Tsung *et al.*, 2004, Owings *et al.*, 2008, Paton *et al.*, 2012). Reduction in the soft tissue strain under the forefoot has also been reported (Lott *et al.*, 2007, Ibrahim *et al.*, 2013), with a reduction in the mean pressure in the same areas. Many authors suggest that this pressure reduction results from a corresponding increase in total surface area (Albert&Rinoie, 1994, Bus *et al.*, 2004, Mueller *et al.*, 2006, Raspovic *et al.*, 2012).

A medial arch support has proved to be highly effective in transferring load from adjacent regions to the medial midfoot (Novick *et al.*, 1993, Brown *et al.*, 1996, Bus *et al.*, 2004). However, although Paton *et al.* (2012) found a significant increase in the total contact area, it was reduced by 50% at six months follow-up. This contact area reduction, linked to the fact that the pressure remained lower, led them to question the association between the contact area and pressure. However, other authors found no significant changes in peak pressures at this location (Ashry *et al.*, 1997, Uccioli *et al.*, 1997, Postema *et al.*, 1998, Bus *et al.*, 2004). These differing results are likely related to the use of different insoles, subjects, as well as experimental procedures, making it difficult to compare these studies. Nonetheless, there is sufficiently strong evidence to suggest that a medial arch support should be a consistent feature in the design and fabrication of insoles for patients with diabetes and neuropathy (Bus *et al.*, 2004). Consequently, an accurate cast is of key importance to achieve the best replica of foot morphology.

3.6.4 Evidence of ulcer prevention and pressure offloading with insoles

Customised insoles with additions are an effective in preventing ulcers and metatarsal bars are a commonly used addition in offloading insoles. This addition is a raised area behind the metatarsal heads to lift the metatarsal heads, thereby reducing the peak pressures which tend to occur under the metatarsal heads (Hsi *et al.*, 2005, Kang *et al.*, 2006, Mueller *et al.*, 2006), just in front of the metatarsal bar (see section 3.6.3.). It has been suggested that the best approach for offloading a diabetic foot, and therefore preventing ulceration, is by using a combination of customised insoles and a therapeutic shoe (Owings *et al.*, 2008). However, insole design is a complex task, as there are different types of insoles that offer different advantages. Furthermore, there are different additions that can be integrated to the insoles to achieve the treatment goal, including changes in the shape of the insole, such as a metatarsal bar. In addition, a range of materials can be used for insole manufacture, each with different properties, thus there is potential for a wide range of insole designs and therefore, choices available to the insole designer. For that reason, it is of key importance to have an in-depth understanding of how insole design features can affect in-shoe plantar pressures.

3.6.5 Cushioning materials

A broad range of materials is available for manufacturing insoles and their mechanical properties, including the abilities of force distribution, shock absorption and durability, should be carefully considered to achieve the maximal therapeutic effect (Kang *et al.*, 2006). Increasing the thickness is an effective approach to reducing plantar pressure. However, the maximum thickness of material that can be used under the metatarsal heads is limited by footwear depth because excessive depth can depend on the shoe, putting the patient at risk for dorsal ulceration (Owings *et al.*, 2008). The use of soft and cushioning materials has been studied and been shown to be effective for pressure offloading (Healy *et al.*, 2012). In 2007, Paton *et al.* (2007)published the results of a study examining the physical properties of 15 materials used to prevent ulcers in diabetic patients with neuropathy. Of these materials, 6 mm Poron was the most effective, followed by ethyl vinyl acetate (EVA) (Fernandez *et al.*, 2013).

Many of the studies showing that soft and cushioning materials are effective for pressure offloading (Kang *et al.*, 2006, Healy *et al.*, 2012, McCormick *et al.*, 2013) have

used the materials to make complete insoles. An important limitation of these studies was that they did not only use softer materials on the forefoot to improve the offloading. The combination of different material densities would allow both offloading and pressure redistribution. In this thesis, cushioning materials will only be used under metatarsal heads, where higher peak pressures and ulceration are more common. This design is explained in detail in Chapter 5.

3.6.6 Metatarsal bars

A total contact insole, on its own, may not be sufficient to reduce pressure and prevent re-ulceration (Hastings *et al.*, 2007). However, when combined with other additions (e.g. changes to the surface shape of the insole), the offloading effect of the insole can be improved. The most common addition is a metatarsal bar which is a convex shaped form positioned in the region of the metatarsal heads (Hsi *et al.*, 2005). The metatarsal bars are placed just proximal to the metatarsal heads and can redistribute the plantar pressure, decreasing the stress and soft-tissue compression at the metatarsal head, by lifting the bone or not allowing it to plantarflex during the toe-off phase of the gait (Hsi *et al.*, 2005, Kang *et al.*, 2006, Mueller *et al.*, 2006). Metatarsal bars are commonly used in combination with a void, which is a partial cut out under the peak pressure areas. This void is typically located just distally from the metatarsal bar to enhance metatarsal head offloading (Figure 3.5).

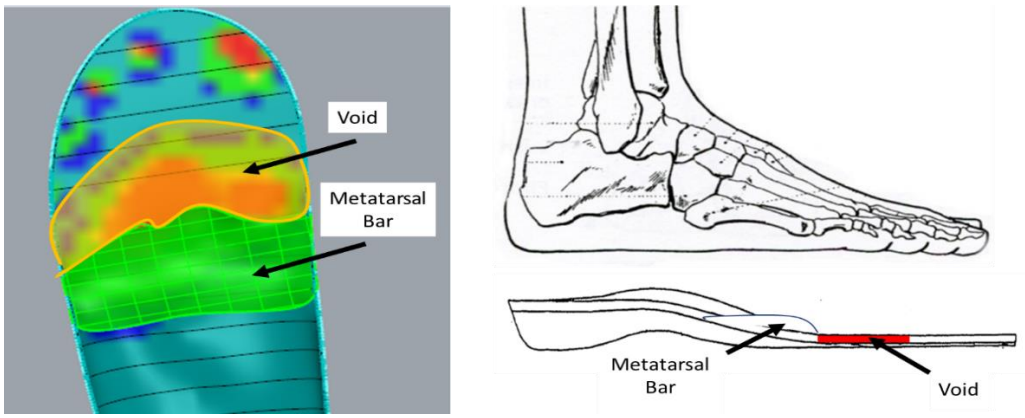

Figure 3.5: Metatarsal bar and void design and position in the insole

Several authors have studied metatarsal bar offloading properties in high-risk patients (Ashry *et al.*, 1997, Bus *et al.*, 2004, Hsi *et al.*, 2005, Mueller *et al.*, 2006, Koenraadt *et al.*, 2012), concluding that metatarsal bars are an effective for offloading pressures under the metatarsal heads, an area that has been associated with ulceration and the presence of high pressures (Ledoux *et al.*, 2005, Patry *et al.*, 2013). However, it is difficult to separate the effect of the metatarsal bar from the effect of the rest of the custom-made insole. Other studies, that have investigated the effect of a metatarsal bar on plantar pressures in healthy people without foot impairments, report highly variable results on the pressure decrease under the metatarsal heads (Holmes&Timmerman, 1990, Hayda *et al.*, 1994, Ashry *et al.*, 1997, Bus *et al.*, 2004, Kang *et al.*, 2006, Mueller *et al.*, 2006). The variation in the published results may be explained by the variability in the subject's response to the metatarsal bar and metatarsal bar differences (shape, size, location, and material properties).

The precise position of a metatarsal bar can have a considerable influence on the pressure reduction under the metatarsal heads, for example, Hsi *et al.* (2005) showed that small changes in the metatarsal bar position led to large changes in pressure. The clinically accepted position of a metatarsal bar has traditionally been 5 mm proximal to the metatarsal heads (Brodtkorb *et al.*, 2008), however, several authors have investigated optimal positioning (Hayda *et al.*, 1994, Hsi *et al.*, 2005, Kang *et al.*, 2006, Mueller *et al.*, 2006, Hastings *et al.*, 2007, Brodtkorb *et al.*, 2008, Koenraadt *et al.*, 2012).

Hayda *et al.* (1994) tested 10 healthy subjects, using 3 different metatarsal pads: large foam, large felt and small felt. They tested each metatarsal pad at 3 different positions: at the metatarsal head base, 5 mm proximal and 5 mm distal. The small felt pad was found to be most effective for offloading, with the distal position associated with the greatest decrease in pressure for all types of pads. In another study, Hsi *et al.* (2005) recruited 10 male participants with a previous diagnosis of metatarsalgia. They tested all subjects with a foam rubber metatarsal pad, in the shape of a domed teardrop, initially placed immediately proximal to the metatarsal head with metatarsalgia and moved by 4.4 mm distally 6 times. They concluded that the greatest pressure reduction was obtained when the metatarsal bar was placed just proximal to the peak pressure. In another study, Brodtkorb *et al.* (2008) recruited 22 healthy subjects taking measurements on one foot that was chosen at random. They tested 2 metatarsal pads, 5 mm and 10 mm high, made

of EVA 55º Shore-A. The metatarsal pad was attached to a Pedar insole just behind the 2nd metatarsal head and moved consistently 5 mm proximally, with the subject instructed to stand on one leg during data collection. They established that when the metatarsal bar was positioned 5 – 25 mm proximal to the metatarsal heads, forces under the 2nd metatarsal head and the toes decrease, while pressures at the metatarsal support region increase. These data support the idea that a correctly placed metatarsal bar will redistribute the plantar pressure from metatarsal heads to the area where the metatarsal bar is placed (Koenraadt *et al.*, 2012).

In a study investigating metatarsal bar position, Hastings *et al*. (2007) found the pressure reduced consistently when the metatarsal bar was positioned between 6 mm and 11 mm proximal to the metatarsal head line. These findings show that variations of more than 6 mm in the metatarsal bar position can have an important effect, significantly decreasing the offloading properties. However, other research has demonstrated that positioning of the metatarsal bar can be inconsistent when placed by either podiatrists or orthotist (Hastings *et al.*, 2007). This inconsistency may explain the variability in the individual response to metatarsal bars observed in other studies (Chang *et al.*, 1994, Ashry *et al.*, 1997, Mueller *et al.*, 2006). Given the importance of accurately positioning the metatarsal bar and the potential for error with manual methods of positioning, metatarsal bar placement should be customised based on quantifiable data, such individual plantar pressure measurements. However, all of the studies described above used standard metatarsal pads instead of customised metatarsal bars based on plantar pressures.

3.6.7 Full insole customisation

To date, there has been only one study by Owings *et al.* (2008), which customised not only the insole but the metatarsal bar shape for an understanding of barefoot plantar pressure patterns. This approach of using pressure data to design the insole may improve offloading as it achieves a more accurate positioning of the metatarsal bar. Owings *et al.* (2008) recruited 22 participants with diabetes and neuropathy to comprehensively evaluate the potential of fully customised insoles by comparing three different insole designs for each participant. Barefoot plantar pressures and foam impression were taken to fully customise the insoles. The first of which was designed with a shell of polypropylene and a plastazote cover, incorporating a standard metatarsal bar. The second

insole was made from 45º shore A EVA and incorporated a plastazote top cover and standard metatarsal bar. The final design was a fully customised insole (35º shore A Micro Puff EVA) based on a foot cast and plantar pressure data with a poron top cover. The metatarsal bar shape was designed using an algorithm that identified a pressure contour and positioned behind peak pressures (Figure 3.6). They also incorporated a void 3 mm deep underneath regions where peak pressures were higher than 1,000 KPa.

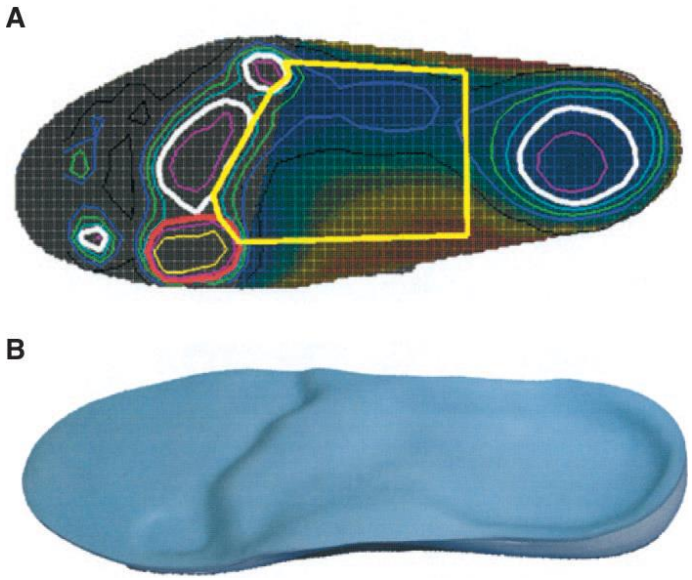

Figure 3.6: Metatarsal bar design process followed by Owings et al. (2008)

Subjects were tested with the three insoles in two different shoes: an extra deep shoe, and a rigid rocker version of the same shoe. Also, a control condition was set using the extra deep shoe with its standard insole. Pressure data was collected with the Novel Pedar in-shoe system at each participant's own speed over a 20-metre walkway. However, only pressures from the first walking step were used for the data analysis. All the trials were averaged for each foot and pressure outcomes were derived from the 1st metatarsal head, 2nd metatarsal head and 3rd-5th metatarsal heads. Any region with pressures higher than 450 KPa was considered as a region of interest. In total, 70 regions of interest across the three masks from each foot of the 22 subjects tested were identified. From these 70 regions, 54 were under the 1st or 2nd metatarsal heads and the customised insole significantly reduced pressures with the pressure based metatarsal bar in 64 of the 70, with 32% more offloading than the polypropylene insole and 21% more than the 45º shore A EVA insole.

These results demonstrate the potential opportunity provided by new technologies for custom insole prescriptions to enhance offloading. In their study, they used a fully customised insole based on foot shape and plantar pressure measurement, however, the plantar pressure data used for the insole design was taken from the first walking step taken by the subject and is not representative of plantar pressures, as several steps are needed to characterise representative plantar pressure patterns (Melvin *et al.*, 2014). Furthermore, in the design process, a 3 mm deep region was removed under areas that the authors considered being high pressure. They defined high pressure as being greater than 1,000 KPa, which may have been too high and they may have missed other areas with high pressures, lower than 1,000 KPa, but still placing the foot at high risk. Moreover, they did not investigate the effect of material as an additional design characteristic for reducing pressure and only studied one metatarsal bar position rather than systematically varying the bar position. Given the limitations of this study, our study was designed to answer the following research questions:

1. What is the effect of systematically varying the metatarsal bar position in combination with cushioning material on in-shoe plantar pressures?
2. What is the mean optimum design?
3. What is the effect of each insole configuration when compared to the control condition?
4. How much additional value is there is in individually choosing specific design features?

3.7 Prediction of the response to insole design

3.7.1 Factors that predict plantar pressures

Plantar pressure is complex and influenced by multiple factors. Although some of these factors are difficult to measure accurately, others may help us understand and predict plantar pressure behaviour, for example, foot structure can affect peak pressure (Ledoux *et al.*, 2005, Guiotto *et al.*, 2013) and peak pressure can predict ulceration, so it is possible that ulceration may be predicted by foot structure. This concept has led some researchers to study different factors to predict plantar pressure behaviour based on feet structural characteristics. In one study, Payne *et al.* (2001) recruited 50 subjects with diabetes and collected socio-demographical variables, different radiographic angles, soft

tissue properties and joint mobility at the ankle and 1st metatarsophalangeal joint, as well as data on neuropathy. They used stepwise regression modelling and found that positive neuropathy scores explained differences in peak pressures under the hallux, 1st metatarsal head and heel. However, they did not obtain any significant results for the pressure-time integral (PTI) prediction from any of the variables studied.

Foot deformity has been found to be a strong predictor of peak pressures. Indeed, Mueller *et al*. (2003) found the presence of hammer-toe on the hallux predicts peak pressures under the metatarsal heads and hallux. In their study, they recruited 20 subjects with diabetes and neuropathy, collecting measures of the foot from spiral x-ray computed tomography and dynamic peak pressures. They used hierarchical multiple regression analysis to predict regional peak pressures under the hallux and each one of the metatarsal heads, finding that the metatarsophalangeal joint angle is the most important predictive pressure variable. Another study, published by Barn *et al.* (2015), suggested that "local variables" such as foot deformity were stronger predictors that "global features" such as Body Mass Index (BMI) or age. For this study, demographic data, foot structure and function were collected from subjects with diabetes, neuropathy and a history of ulceration, and analysed using multivariate linear regression. They concluded that the presence of a local deformity was the largest contributing factor to barefoot dynamic pressures in high-risk diabetic patients. However, they warned that a significant amount of variance in pressure was not explained by the model, suggesting that plantar pressure measurements are required in clinical settings to properly assess an individual patient's risk.

Another approach adopted in the literature is to predict plantar pressures based on biomechanical and spatiotemporal data. Morag&Cavanagh (1999) recruited 55 healthy subjects and collected data on foot characteristics, as well as 3D foot motion and electromyography (EMG) while walking. They found that foot motion influenced pressures under the 1st metatarsophalangeal joint and that hallux pressures were highly influenced by the 1st metatarsophalangeal joint range of movement (ROM). Payne *et al.* (2001) studied 50 subjects with diabetes and neuropathy, also showing that the 1st metatarsophalangeal joint ROM is important in determining pressures under the hallux. In addition, the neuropathy-related variables can influence plantar pressure under the diabetic foot.

Taken together, the results of the studies described above illustrate that plantar pressures can be influenced by a range of different factors, including individual characteristics, such a neuropathy, as well as specific structural variables, such as those describing foot structure and deformity. In addition, biomechanical variables describing movement characteristics, such as the ROM of the 1st metatarsophalangeal joint have also been found to influence plantar pressures. It is possible that, as well as directly influencing pressure, these factors may also dictate individual responses to different insole designs. If this is the case, then clinical decision tools are required which can measure appropriate variables and use this information to identify the best insole design for a given patient. This concept is explored in more detail in the following sections.

3.7.2 Mathematical models for predicting individual plantar pressure responses to an insole design

It has been suggested that computational models may be an effective tool for predicting plantar pressure responses to a specific insole design (Actis *et al.*, 2006). In line with this, several studies have used finite element models (FEM) to predict the effect of different insole designs. Finite element modelling is based on the fact that complex geometries, such as the surface of an insole, can be divided into very small subdomains, each of which is modelled individually. For the problem of predicting plantar pressures, the insole is divided into small subdomains and the mathematical equations which describe how the insole material responds to an applied load are solved in each domain. These solutions are then matched together to obtain a mathematical description of pressure distribution across the insole for a given foot shape and set of insole characteristics (surface geometry, compressibility, etc). Using this approach, it is possible to investigate the effect of different insole designs without extensive experimental work.

Using 3D FEM analysis, Barani *et al.* (2005) compared offloading properties of different insole materials. They concluded that silicone gel was the optimum material to reduce stress concentration and was also good for shock absorption, with Polyfoam and Plastozote being viable alternatives. In another study, Goske *et al.* (2006) investigated 27 insole designs with combinations of three insole conformity levels (flat, half conforming, full conforming), three insole thickness values (6.3, 9.5 and 12.7 mm) and three insole materials (Poron Cushioning, Microcel Puff Lite and Microcel Puff). Their FEM model

was developed to predict pressures during the early support phase of gait and predicted plantar pressures were validated through comparison with experimental data collected from a single subject. Although predicted peak pressures were slightly higher than those measured experimentally, Goske *et al.* (2006) demonstrated the potential that FE models have for furthering understanding the effects of different insole design characteristics.

Chen *et al.* (2003) used FE modelling to investigate the effects of total contact insoles on plantar stress distribution. They concluded that total contact insoles can reduce high pressures at regions, such as the heel and the metatarsal heads, and also redistribute the pressure to the midfoot region when compared with flat insoles. In another study, Cheung&Zhang (2005) used FE models to investigate the effect of material stiffness of flat and custom moulded insoles on plantar pressures and stress distribution in the bone and ligamentous structures during balanced standing. They established that a custom-moulded shape was more important for reducing peak plantar pressure than the stiffness of the insole material. Actis *et al*. (2006) developed a range of FE models of the foot and showed that bone, tendon and fascia structure, as well as soft tissue properties, need to be incorporated into the model if plantar pressures are to be predicted accurately. With these components, their model was able to accurately predict pressure distribution in both barefoot and with shoe and insole in the metatarsal head region.

The studies described above demonstrate the potential of using mathematical models to predict plantar pressures. Given that these models incorporate structural characteristics of the foot; they offer the potential to predict individual patient responses for a range of insole designs. However, these models are complex to implement, requiring precise structural characteristics of individual feet and the computations can take long periods of time. Therefore, in their current form, they are not appropriate for wide-scale clinical use. However, the aim of this work is to facilitate the development of a clinical decision-making tool which can guide clinicians on insole design choice. As such, a more in-depth understanding of the effects of individual factors which may lead to differences in pressure responses to the same insole design is required. To date, there has been limited work in this area which, as explained above, has focused almost exclusively on finite element models. Many different factors could influence the response to insole design and given the paucity of research in this area, a study was designed to investigate the potential

modifying effect of a number of different variables. A rationale for how and why each of these variables may modify insole design is provided below.

BMI (body mass index): A higher BMI indicates a higher weight for a given height and would be expected to lead to higher pressures under the foot. Interestingly, previous research has only found weak correlations between BMI and peak plantar pressures (Barn *et al.*, 2015) in patients with diabetes and peripheral neuropathy, indicating that increased body weight is somehow redistributed across the plantar surface of the foot, minimising local peak pressures. It is possible that this redistribution may lead to differences in the way individuals respond to the same insole design.

Arch height: Foot structure has been shown to be a predictor of plantar pressure (Barn *et al.*, 2015). One of the most common foot deformities is a change in arch height, and this characteristic (cavus foot) is common among patients with diabetes (Ledoux *et al.*, 2005). A higher arch height entails a smaller contact area of the foot with the ground while walking, resulting in redistribution of peak pressures across the foot. Again, this redistribution may lead to differences in the way individuals respond to the same insole design.

Ankle joint mobility: The presence of neuropathy can reduce the mobility of selected joints in the foot, with the ankle joint being the most commonly affected (Guiotto *et al.*, 2013). This lack of mobility has been associated with high peak pressures and also, a higher PTI on the forefoot (Zimny *et al.*, 2004). Moreover, lack of mobility In the ankle can lead to an elevated time-dependent load of the forefoot (Fernando *et al.*, 1991), a variable which has previously been found to be one of the predictors of plantar pressure (Payne *et al.*, 2001). Given its influence on peak pressure, ankle joint mobility may also affect individual responses to insole design.

1st MPJ mobility: Similarly to the ankle, the 1st MPJ is one of the most common joints of the foot affected by neuropathy (Guiotto *et al.*, 2013). Birke *et al.* (1995) reported that when this joint becomes restricted, PP under the 1st metatarsal head rises in patients with diabetes. However, Bryant *et al.* (1999) reported that peak pressure under the 1st MPJ was significantly reduced in subjects with hallux limitus compared to controls. The relationship between the 1st MPJ ROM and PP behaviour is controversial, but several authors have concluded that it acts as a PP predictor (Payne *et al.*, 2001, Menz&Morris,

2006, Turner *et al.*, 2007, Rao *et al.*, 2010). Given the important function role this joint plays during the push-off phase of the gait, it may also influence the response to a given insole design.

Subtalar joint mobility has been documented to have reduced passive mobility in subjects with diabetes (Fernando *et al.*, 1991), which may result in a reduced calcaneal eversion and inversion ROM during walking. This loss of mobility may entail a decrease in the forefoot mobility because it is believed to ‘‘unlock’’ the midfoot to allow greater mobility (Blackwood *et al.*, 2005). Rao *et al.* (2007) found decreased eversion ROM in subjects with diabetes. Subsequently, they reported associations between decreased subtalar ROM and PP increase on the medial forefoot (Rao *et al.* (2010).

Tissue stiffness: plantar soft tissues, particularly on the forefoot and heel regions, are specially structured to provide cushioning and shock absorption during walking. Stiffening of these tissues is associated with diabetic neuropathy and has been found to significantly increase the plantar pressure and internal stress, thus has been proposed to be an additional predictive factor of ulcer development (Pai&Ledoux, 2010, Sun *et al.*, 2011, Periyasamy *et al.*, 2012, Patry *et al.*, 2013), specifically increased tissue stiffness has been associated with higher peak pressures and ulceration. DM has also been shown to lead to a stiffening of the soft tissues on patient’s feet. However, this effect of the stiffening will vary between individual patients and so may affect how individual feet respond to different insole designs.

Ankle joint maximum angular velocity: the decrease on ankle joint ROM present in patients with diabetes and neuropathy leads to an abnormal joint motion (Fernando *et al.*, 2013). This lack of mobility in the ankle can also lead to an elevated time-dependent load of the forefoot (Fernando *et al.*, 1991), a variable which has previously been found to be one of the predictors of plantar pressure (Payne *et al.*, 2001). Moreover, Rao *et al.* (2010) found decreased ankle moment and power, which were associated with increased plantar loading in patients with diabetes.

1st MTJ joint maximum angular velocity time: as with ankle joint velocity, there is a reduction in joint mobility on the 1st MPJ on patients with diabetes and neuropathy (Fernando *et al.*, 2013). The ROM in this joint and its motion during gait has been previously associated with PP (Turner *et al.*, 2007, Barn *et al.*, 2015). Given the

consequences that prolonged PP may have in neuropathic tissues, it is important to further understand the influence of this variable in PP.

The variables identified above all have the potential to influence individual responses to different insole designs. Moreover, each of these factors is amenable to measurement in a clinical scenario, either via a simple clinical test or with a miniaturised gait laboratory (Mifsud *et al.*, 2014). More insight into how these factors affect individual plantar pressure responses would facilitate the development of a clinical decision tool which could guide clinician's choice of insole design characteristics. This idea is explored in Chapter 8, which investigates the factors that influence the patient's response to insole design.

3.8 Scope and limitations of the project

This thesis has been designed based on the framework given by the European Union project SMARTPIF. The University of Salford's role in the project was to collect the morphological, biomechanical and pressure data from a cohort of high-risk patients. Given the external nature of the funding, the project had two main limitations; the first being that the focus should be on pressure offloading using insoles, however, the project did not stipulate the specific design of the insoles. The other limitation was the study sample, the target population was defined as "high risk", but did not state which groups of medium or high-risk patients should be chosen. The author took the lead on all the different arrangements needed to design the different studies for this thesis, the recruitment and data collection, processing and analysis.

First, a literature search was performed in order to identify a high-risk population that would benefit from wearing customised insoles. Patients with diabetes and neuropathy were selected as the target population given the serious and disabling complications that this disease has on their feet. This population can be classified as low, medium or high-risk population based on the different complications that they suffer according to the NICE guidelines (NICE, 2016). Therefore, it was decided to recruit subjects with diabetes and neuropathy, but with no history of ulceration, which are considered as medium risk population. The aim behind this choice was to prevent the ulceration, that would move them into the high-risk population group, with the use of

insoles which have been shown to prevent ulceration (Owings *et al.*, 2008). Accordingly, a further literature search was then performed in order to identify the most commonly used insole designs to prevent ulceration, but no consensus was found regarding the insole design. The most common approaches were metatarsal bars and cushioning materials, but there were no reports of them being used in combination to understand their effects. Accordingly, they were selected to further investigate their effect when combined.

The project had some specifications about the data to be collected, such as plantar pressures and motion data. However, it was decided to also include clinical tests required to select the insole design for each participant and to better define the sample. Once the data set and the protocols were defined, an NHS ethics application was submitted. When the ethics approval was granted (REC: 13/NW/0331), the recruitment was started with the help of a radio advert and the NHS. All patients included in this study regardless of how they were recruited underwent a screening process (explained in detail in section 5.1.2). All data collection, processing and analysis for this thesis were performed at the University of Salford.

The four main studies which constitute this PhD are summarised below:

Study 1: An exploration of current practice in relation to engagement with technology

Insoles are normally prescribed to patients by podiatrists as part of their care package. In clinical practice, the choice of treatment tends to be based on what is considered appropriate for the foot deformity and/or symptom, the type of footwear worn by the patient and the practitioner's preferences. Moreover, there is no consensus on what treatment should be provided to achieve optimum results. However, although there are general guidelines that foot orthosis and pressure relief should be provided to medium and high-risk patients, they are not detailed or standardised. Consequently, the diagnosis and prescription process is currently an experience-based trial and error task. Moreover, no factors have been identified which influence the professional's decision making. These influencing factors and the different steps taken by the professional to treat and prevent the serious consequences of this disease need to be clarified. Furthermore, it is important to ascertain which variables the practitioners base their prescriptions on, what the process of assessment and diagnosis is, and where technology fits within current practice.

Study 2: Reproducibility of plantar pressure collection using a wireless in-shoe pressure device

Reproducible pressure measurement methods are required to interpret the findings of studies aimed at quantifying differences in plantar pressure between different insole designs. However, previous reproducibility studies have focused on healthy subjects and tested flat insoles, rather than insoles contoured to match the shape of the foot. It is possible that subjects with diabetes and neuropathy may have a less repeatable gait pattern than the healthy subjects studied in previous reproducibility research. Therefore, this study was undertaken to quantify the level of reproducibility of plantar pressure measurements in patients with diabetes and neuropathy. A total of nine subjects were tested using ten insole designs (Chapter 6), and SEM and ICC statistics were used to quantify the level of reproducibility for each design. Subsequently, this was used to facilitate interpretation of the results from quantitative Studies 2 and 3, outlined below.

Study 3: Understanding the effect of systematically varying insole design characteristics on in-shoe plantar pressure

Customised insoles and metatarsal bars have been shown to be effective for offloading peak pressures in people with diabetes and neuropathy. However, previous studies have not tested individually positioned metatarsal bars, nor is there a complete understanding of where the metatarsal bar should be positioned relative to the region of peak pressure. Furthermore, although cushioning materials have been shown to reduce peak pressures, it is not clear how to combine specific cushioning materials with a customised metatarsal bar for optimal offloading. For these reasons, this study sought to understand the effect of systematically varying the position of a fully customised metatarsal bar and the type of cushioning material. A total of ten insole designs were produced (Chapter 7) and tested on a total of sixty subjects with diabetes and neuropathy. The results of this study were then used to make clinical recommendations on insole design for people with diabetes.

Study 4: Identifying variables which may affect an individual's response to insole design

Previous research has shown that there can be differences in the way individual patients respond to the same insole design. It is possible that these differences are the result of different structural and biomechanical characteristics which have the potential to influence pressure behaviour and therefore, the magnitude of offloading. However, although previous research has investigated factors which may predict plantar pressure during barefoot walking, there is little research aimed at understanding which factors could determine individual patient responses to different insole designs. Therefore, this study (Chapter 8) was designed to investigate how a range of variables, including joint stiffness, tissue stiffness and joint movements, impacted on pressure responses. This information was then used to make recommendations in Section 8.7.3.

4 An exploration of current practice in relation to engagement with technology

4.1 Introduction

A number of systemic conditions present with complications that place the foot at risk of developing limb-threatening conditions, such as ulceration. One of the commonest conditions is type 2 diabetes, which is associated with neuropathy and altered foot architecture, resulting in the foot being at 'high risk' as the subsequent ulceration can lead to amputation (Paton *et al.*, 2011, Hennessy *et al.*, 2012). Elevated plantar peak pressures (PP) have shown to be a risk factor for ulceration in the diabetic foot, particularly when in presence of foot deformity and peripheral neuropathy (Bennetts *et al.*, 2013). Insoles represent an effective approach to offloading PP and therefore, to help to prevent ulcer formation (Paton *et al.*, 2011). Accordingly, in order to prevent ulceration, podiatrists may prescribe insoles as part of the care plan for such patients. However, insole design is a challenging task that, if not carried out appropriately, could increase the risk of ulceration in diabetes. Clinicians must take into consideration the potential effects of many factors when designing an insole, including the patient's weight, occupation and footwear. In addition, it is often the case that when similar foot pathologies are prescribed the same type insoles, the response varies between individuals (Kang *et al.*, 2006). In clinical practice, the choice of the insole is directed by what may be considered appropriate for the specific foot disorder, that is, the type of footwear worn by the patient as well as the practitioner's preferences (Williams *et al.*, 2016). Hence, there is no consensus insole design for maximum foot health improvement.

There are general guidelines that recommend the use of insoles and pressure relief strategies in high-risk patients (Pinzur *et al.*, 2005, Group, 2014). However, these guidelines are based on expert opinion and experience as opposed to empirical research, consequently, they lack specific insole design criteria, leading to variable clinical practice as practitioners base their decisions on personal preferences and experience which results in variable clinical practice.

The Root model of foot function (Root, 1973, Root *et al.*, 1977) forms the foundation of biomechanics training for preregistration podiatrists and is continued to be used in post registration practice. Interestingly, Jarvis et al. Jarvis *et al.* (2012) found that practitioners change their practice and decide which protocols they want to use as they gain experience, for example, the use of the Foot Posture Index (Redmond *et al.*, 2006). Another factor that may influence practice is the use of technology to enhance patient care given that there is evidence to suggest that 3D foot scanning is more repeatable and reliable than plaster of Paris and foam impression boxes (Telfer *et al.*, 2012). In addition, devices that collect plantar pressure data may improve the accuracy of both the diagnosis and insole design procedures. However, this technology is not readily available in the clinical setting and appears to be limited to research environments. Nevertheless, the final decision lies with the practitioner, which is often based on personal experience and preferences concerning the choices in relation to tools for the assessment, diagnosis, and prescription of orthoses. This may also change between patients and categories of patients.

This freedom in prescribing can hinder the standardisation of orthotic prescriptions and the creation of guidelines. However, although the theoretical base of their practice is relatively consistent, all the factors and experiences that influence the decision-making are less so. Despite insoles being one of the most popular treatments for certain foot pathologies (Landorf&Keenan, 2000), the decision-making processes and tools used for designing insoles remain unclear. Therefore, there is a need for a better understanding of the different tools available to professionals, as well as the decision-making processes, that aid in the diagnosis of foot pathologies and the design of appropriate orthotics. This study aimed to identify 1) what variables practitioners base their prescription design on, 2) what processes are used for assessment and diagnosis of structural foot pathologies and 3) how technology fits within current practice. A qualitative research method was employed to obtain the relevant data.

4.2 Objectives

This study addressed three primary objectives:

1. To gain insight into the aims of the practitioners when providing insoles in relation to both theirs (foot geometry, motion control, pressure redistribution, accommodation of deformity) and their perception of the patient's clinical need (usability, outcome).
2. To identify which factors influence the assessment of patients and the specific design of the insole (including the materials used in their manufacture).
3. To gain insight into how technologies can facilitate the achievement of patient and practitioner goals.

4.3 Methods

4.3.1 Recruitment

Ethical approval was obtained from the University of Salford ethics committee (HSCR12/62). A total of 17 podiatrists with a broad expertise on lower limb pathologies and insole prescription were actively recruited to take part in this study. These participants were members of the North West Clinical Effectiveness group and the National Podiatry Network. Also, orthotists were recruited to participate in the study to represent the other main profession that normally prescribes insoles to their patients in the UK. All participants invited to take part in the study prescribed insoles in their day to day clinical practice and had a minimum of two years of clinical experience. An information sheet explaining the aims of the project and their role within it was sent to each participant after they agreed to take part in the study. Prior to the focus group and once they read the information sheet, all the participants were asked to provide informed written consent.

4.3.2 Data collection

Focus groups were selected to provide the qualitative approach for this study and were considered appropriate to answer the research questions. There are other qualitative approaches such as one-to-one interviews or Delphi models, but they were deemed inappropriate for this type of study. One-to-one interviews illustrate the opinions and

preferences of only one practitioner as opposed to a group. On the other hand, the main aim of the Delphi approach is to reach a consensus from a group of participants. However, the main purpose of this study was to gain a better understanding of what influences clinical practice and the role of technology rather than achieving consensus. Therefore, a focus group provided the ideal environment for a friendly, open dialogue where different ideas, habits and preferences on diagnosis and prescription were presented and discussed, but not necessarily agreed on.

There were two sets of focus groups with eight participants in each set (one participant could not attend on the day he was assigned). The focus group was led by a co-researcher who was an academic with previous experience in conducting focus group discussions and with clinical experience in this area. The dialogue was digitally recorded and field notes were taken by myself and an additional co-researcher. Each focus group commenced with a presentation of the main aim of the study and the latest technological developments for insole and footwear provision. Also, an explanation of the format of the discussion was given, including an agreement that all participants should be allowed a voice and that all opinions should be respected to ensure that there was no conflict. Then, an opening question was used to initiate discussions:

- "What factors influence the orthotic or footwear prescription in relation to your aims and the patient's expectations?"

Further trigger questions were used to help guide the dialogue including:

- What types of foot orthoses and footwear would you prescribe for these specific conditions?
- What designs of foot orthoses do you use and why?
- What casting methods do you use?
- In relation to terminology - When does bespoke become bespoke?
- Is the term right? Should it be customised v off the shelf - As both could be considered bespoke in relation to a 'bespoke prescription'
- Do you use any technology in the assessment of your patients?
- What materials do you use for functional foot orthoses and why?
- What materials do your use for accommodative foot orthoses and why?

- What influences the footwear choice?
- What about the specific design features of the footwear?
- What influences this decision in relation to the patient's medical history?
- What are the influences in relation to foot / lower limb structure and function?
- What are the main steps of your assessment of a patient?
- Are there any other patient focused influences on your decision making?
- What variables in orthotic prescription do you think predicts success?
- How do you measure /evaluate outcomes?
- What Problems in the assessment and prescription process do you find are the most challenging?
- What do they think patient's opinions of their foot problems and treatments are?
- What factors influence their understanding and engagement with foot orthoses/ specialist footwear?
- What would technology/Tools you like to have in your practice?
- Why don't you have them?
- What do you think the benefits would be?

The presentation introducing the focus group topic lasted for about 15 minutes, and the discussion after lasted between one hour and a half to two hours, depending on its evolution.

4.4 Data analysis

The data generated from the dialogue were transcribed verbatim by a specialist transcription service. The transcripts were then analysed using an iterative approach to thematic analysis as described by (Attride-Stirling, 2001, Darlington, 2002).The results were analysed and presented in two stages. First, the preliminary themes were identified from my field notes only and secondly, the preliminary themes were then compared with those found by the co-researchers. After discussion, an agreement was reached providing the final themes, subthemes and a final global theme as an overall conclusion (section 4.5).

Following data analysis, the results were sent to the focus group participants for verification and any additional comments. All participants agreed that the different

themes extracted represented the discussion and that the interpretation was correct. There were no additional comments. The participant names were then replaced with a pseudonym in order to maintain anonymity for the purposes of this thesis and any subsequent publications.

4.5 Results

The preliminary themes identified were developed using the iterative method into final themes (Table 4.1).

Preliminary themes	Final themes
Materials used	What current practice behaviour is based on
Casting techniques	Components of current practice
Insole design	Influences on choice of foot orthosis • Materials • Casting techniques • Design of insoles
Types of insoles and footwear	Barriers to engagement with technology
Technology	Perceptions as to how technology could enhance insoles/footwear design
Difficulties	Perceptions as to how technology could enhance the evaluation of orthosis
What they want	Perceptions as to how technology could provide information for practitioner and patient
-	Perceptions about the usability of technology in clinical practice

Table 4.1: Preliminary and final results obtained from the reiterative analysis of the data collected during the focus groups

4.5.1 Preliminary themes

As mentioned previously, the transcripts were analysed using an iterative approach to thematic analysis and I conducted the first analysis from my field notes recorded during the focus groups, resulting in seven different themes:

Preliminary theme 1 – Materials used:

Practitioners often experience problems acquiring some materials due to budget or distributor restrictions. EVA is most commonly used and is considered to be a 'traditional' material for many orthotic designs. Practitioners feel EVA works well and know how to combine it with other materials to achieve good results. It is also relatively cheap and easy to obtain. However, it deforms easily, which highlights the importance of using the right material density. Plastazote is another popular material which is effective, light, long lasting and more flexible and easy to work with than other materials such as polypropylene. Combining different materials in order to obtain control and cushioning is a common approach, with practitioners often realising these different combinations by trial and error. Accordingly, they use specific combinations of materials rather than trying new materials.

Preliminary theme 2 - Casting techniques:

The semi-weight bearing foam box is the most popular casting technique because it is relatively fast and clean. Plaster of Paris, on the other hand, is only used for complex patients. Traditional casting techniques are more popular than 3D scanners because they allow the practitioner to correct the foot position, which is key to achieving the prescription's target. In addition, 3D scanners are very expensive to acquire, so most practitioners in the public sector cannot afford them.

Preliminary theme 3 - Insole design:

The first step in the insole design process is the identification of the origins of the problem and the treatment approach for that particular problem. This is a difficult task as many variables should be considered that may influence the prescription's effect, such as activity, joint mobility, medication or comorbidities (e.g. rheumatoid arthritis). Furthermore, practitioners agree that "normal" does not exist so there is no need to set the foot in a perfect biomechanical position. Consequently, if the patient has altered biomechanics of the foot with no symptoms, no treatment will be prescribed.

The practitioner's experience influences the prescription, but they agree that simple prescriptions normally work better than those that are more complex. Also, most

patients can be treated with simple insoles which are more likely to fit the patient's expectations and will enhance adherence to the treatment, as many of them are reticent to wearing insoles.

Preliminary theme 4 - Types of insoles and footwear:

Standard insoles are effective for most patients; they are also cheaper, faster and easier to obtain than customised insoles. Therefore, they are often the first option for patients without deformities. However, each patient is different and these differences have to be considered when prescribing.

Footwear restricts insole design and patients are not likely to wear therapeutic footwear. Therefore, it is best to show the patients pictures of the footwear they should wear to make sure they know how it looks and agree to wear it.

Preliminary theme 5 - Technology:

Devices, including pressure platforms or in-shoe pressure devices, and technology such as CAD-CAM are too time-consuming to use and are therefore rarely utilised, often only used for complex patients. Furthermore, 3D scanners are too expensive and require specific software and training before use. Practitioners also find that technology can have too much influence on their decision-making processes whilst prescribing and they prefer to make their own diagnoses and prescriptions.

Preliminary theme 6 - Difficulties:

Practitioners tend not to try new methods because they feel more comfortable with those familiar to them. Also, dissemination of practice among practitioners is not very common because their prescriptions are based on experience rather than science. An additional problem they face is the limited budget in the public sector, where patient satisfaction is the main goal.

Preliminary theme 7 - What do they want:

Practitioners would like to be able to make custom-made insoles for all patients with no budget or material restrictions and with good communication with the laboratories.

Regarding technology, they would like to see what happens inside the shoe when the patient is walking with and without the treatment; to assess it and to be able to show the patient. Also, they would like wireless, fast, simple devices for clinical practice only, without complex outcomes, which could be time-saving in predicting prescription outcomes.

4.5.2 Final themes

The independent first analysis that each of the researchers performed were then combined and discussed. A final agreement was reached with eight different main themes and a final global topic. There were three themes in relation to current practice (1-3) and five on contextualised opinions on the use of technology in clinical practice (4-8).

Final theme 1 - What current practice behaviour is based on

All practitioners agreed that current practice behaviour is experience based, influenced by "trial and error". Also, how and where they were trained is a major factor, for example, podiatrists have a symptomatic approach to treatment whereas orthotists also treat the biomechanics whether symptomatic or not. As Duncan said:

"...I trained at XXX but my colleague trained at XX and we do differ in our approach and choice of materials in particular…"

Also, Mary said:

"…once you have been trained then it's a matter of trial and error…what works gets repeated and what doesn't…well you bin that idea. Then all this becomes your personal preference."

They take published research and make sense of it in their own practice, which gives them a feeling of ownership rather than being told what to do by researchers. The workplace also has a significant influence on their practice behaviour. In line with this, Adam added:

"…we need to feel that there is a sense of ownership rather than being told what to do by researchers… when I read papers I have to apply it to what I know works and often that is in conflict… I then dismiss the research."

Additionally, the type of service they work in (e.g. MSK or ICAT) or political issues, such as changes in the service structure, may influence the way they diagnose and treat patients. As Sarah said:

"…you have to retain your professional identity, and so this leads to behaviours becoming entrenched rather than changing to keep up with new practice…"

Final theme 2 – Components of Current Practice

Listening to the patient and history taking represents a huge part of the consultation and is seen as the foundation of success. It helps to focus on the patient and fit what he wants with what the practitioner wants. As Joan stated:

"Listening to the patient and history taking is a huge part of the consultation (time)…it is part of getting to the correct diagnosis and patients expect it and I see it as the foundation of success… then the 'hands on' bit has to be quick, so I tend to use foam boxes for casting or off the shelf insole."

Others agreed with this and Dan added,

"…the consultation is where you can educate the patient, and that is as important, if not more so, than the orthotic…if they understand then they will change their footwear, and then that's half the battle."

The main target of the prescription is to ensure that the patient is happy and reach an agreement with them, in particular about footwear, as Sam commented:

"...we listen to what patients want and then make that fit with what we want. I spend a lot of time engaging with the patient...counselling them on the effect of weight and things like their type of activity..."

The first treatment option is the simplest, to achieve the maximum correction with the simplest and most comfortable insole design. However, clinical practice is very variable as it is based on the practitioner's experience and training. All agreed with what Joan said:

"...this may sound expensive and time-consuming...at least we can give something on the day, or if you are unsure of whether an orthotic is going to work then, you can give it a go with the temporary one."

Final theme 3 - Influences on the choice of insole:

Sub-theme – materials

EVA is the most commonly used material as it is durable, easy to use and acquire and is cheap. Furthermore, practitioners are accustomed to using this material, they are familiar with how to work with it and know that it is effective for their prescription targets. Therefore, despite knowing about new materials they continue to use EVA.

Material choice is based on the clinical aim of the prescription and the combination of hard and soft materials is a popular approach to providing both motion control and cushioning. In addition, patient's characteristics, such as activity and weight, are important when choosing materials. The underlying pathology determines the aim of the orthotic and the length of time the patient is required to use it (e.g. short term for plantar fasciitis or long-term for rheumatoid arthritis or diabetes).

Sub Theme - casting techniques:

The aim of the orthotic is one of the main factors for the choice of casting technique. Joint mobility also has to be taken into consideration as the foot has to be mobile in order to achieve correction. Therefore, Plaster of Paris is commonly used for feet with low mobility, while a foam box is used for feet with good joint mobility. In

addition, the practitioner's preferences and habits strongly influence the casting technique selected.

The simplest approach is always preferred in daily practice, consequently, casts are only used for complex patients. On the other hand, patients without deformities or who are not high risk will be most likely prescribed standard insoles that do not require taking a cast.

Sub Theme - design of insole

The main factors influencing design are the diagnosis, the aim of the treatment and the treatment outcomes that the patient expects. For non-complex pathologies, standard insoles are the first choice as they are cheaper and easier to fit and patients do not have to change footwear. Standard insoles are also much quicker to supply as the wait for appointments is lengthy.

"...I often compromise... Don't always do a full correction…an example is the height of the arch as it may irritate, shoe choice may not be suitable, so full correction isn't possible."

Adam agreed and added:

"...we may be aiming for pressure redistribution, improve function, reduce shock and shear or combinations of all of these…this defines what type of device and the materials."

Patients' characteristics such as activity, joint mobility or BMI are important when choosing the insole material. Also, medication plays a major role in reducing the patient's symptoms.

The following themes emerged from the part of the focus group conversations around technology.

Final theme 4 – Barriers to engagement with current technology:

The main barrier to engaging with technology is that it is too time-consuming to set up and use, requiring specific training as stated by Robert:

"We are not trained in technology…we would spend too much time to set up and to interpret, I don't think patients expect it…this makes it slow to use, and maybe wrong information will be collected."

In addition, devices are only compatible within the same brand and the cost is too high. Furthermore, technological devices are not designed for clinical purposes and provide many complex, unnecessary data. Aligned to this Sarah said:

"…it provided too much info…its ok for research but for clinical use it is difficult to navigate through all of it…you normally use 10% of the software because most of the information is not useful for clinic, it is for research…it also doesn't replicate the foot in sufficient detail. The manufacturers don't produce a kit that is clinically useful".

Practitioners only find technology useful for complex patients or those with problems with the treatment prescribed. They also feel that rather than enhance their skills, technology replaces them.

Final theme 5 – Perceptions as to how technology could enhance insoles/footwear design

They agreed that an algorithm to evaluate the insole and footwear effect while being used by the patient would help inform the patient and assess the outcomes of the prescription, as well as the effect on the upper limb or back. It would also assist with mapping foot types, patient activities and orthotic design trends, as well as the patient's adherence to the treatment.

Basic templates of insoles and shoes that can be modified (adding or removing additions) depending on the patient's needs was another popular idea. These templates

should be based on real foot shape, providing a "perfect fit for the foot and the shoes". As Dan said:

"Shoes have to be an essential component… we need an algorithm for insoles AND shoes in the context of the patient's life…also something to inform the patient what a good shoe is and then the insole would go into retail footwear based on foot dimensions and volume."

Graham agreed and added:

"…templates so you just have to introduce foot measures without casting, and that the software tells you the best design and material".

In addition to this, Peter suggested a library of shapes (overall design and additions) but

"… not too many as it would get too complicated to navigate through in the time we have".

Finally, they also suggested that technology could enhance the characterisation of the properties of materials, as well as provide information on how combinations of materials (two or more together) could be used. This improved characterisation of multiple layers of different materials would help in deciding what the optimal combinations would be for specific cases.

Final theme 6 - Perceptions as to how technology could enhance the evaluation of orthoses

Practitioners agreed that a device that helps assess the effect of the insoles before the patient leaves the clinic would be of great help. This would contribute to reducing the number of appointments and increase the patient's satisfaction with the treatment. Aligned with this idea Neal said:

"…to be able to assess how the insoles are working before the patient leaves the clinic… in order to make adjustments that would normally be done at the review when

problems might have occurred…could predict this…and very useful when you don't have a review appointment."

There was agreement that being able to see what happens inside the shoe while the patient is walking, before using the insoles and after, would help both practitioner and patient.

The other main suggestion was a system to predict outcomes from both the shoe and insoles. Also, they were interested in having a better understanding of the effect that each one of the additions has on the insoles. They think that only the effect of the insoles can be predicted, not the success, as there are too many extrinsic factors that influence it as Joan commented:

"…. you can only predict the effect of the orthoses, not the success as there are too many extrinsic factors that influence this…you can have the same foot type, but if you put that in two different patients there is a chance that you will get two completely different responses by doing exactly the same thing".

Final theme 7 – Perceptions as to how technology could provide information for practitioner and patient

To support the practitioners continued education, it was agreed that it would be useful to interpret or translate the research into the clinical setting. Also, a tool that would help them share practices and results with each other (in the same professional language) across different services and professionals would be helpful.

To help provide information to patients about their pathology and the treatment they have been prescribed, practitioners think that visual schemes of what comprises the treatment, how they work and their final look, would be the best approach. Pictures of appropriate footwear would be useful tools to help patients understand the footwear options available to them. Donna said:

"…If we could check if the insoles are working inside the shoe, and that way be able to show the patient the treatment is working correctly…it may increase compliance."

Aligned with this, Lesley suggested:

"A visual for what is a good shoe (components identified and then jigsaw together as a whole picture…patients see shoes as a whole unit, not the component parts, and so this 'deconstruction' would be a useful visual aid."

A system that allows the follow-up of patients would be helpful to avoid unnecessary appointments. Also, a system which can 'flag up' which patients require referral to specific practitioners (such as physiotherapist) would be beneficial.

Final theme 8 – Perceptions about the usability of technology in clinical practice

Any device used in clinical practice must be fast and easy to use, providing results that are simple to interpret with simple clinical terminology. Technology should save time and be reliable in order to be a good investment. It should also be customizable with bespoke menus and templates so that each practitioner can have their own setup. One of the main ideas was the need for a wireless in-shoe pressure device without cables.

Global theme

The final global theme was agreed between myself and co-researchers and endorsed by the participants as reflecting the meaning of all the results.

Current orthotic practice does not embrace technology, with choices in orthotic design being variable between practitioners and subject to many influences. The overarching barrier to their engagement with current technology is that it is not fit for purpose in the clinical environment, while practitioners do have a desire for technology that is usable and enhances the assessment, the interventions, the clinical outcomes and patient engagement throughout these processes.

4.6 Discussion

The aim of this study was to gain a better insight into the main components of orthotic practice. To this end, the different factors that influence clinical decision-making and the role of technology within it were identified. In order to achieve this main objective, focus groups were selected as the best methodological approach. Other qualitative methods were considered but dismissed as they were not considered appropriate to address the research objectives. One method contemplated was one-to-one interviews, but they would only illustrate one participant's opinion or belief at a time, which would not be representative of all the practices across the country. The Delphi method was also considered given that this approach requires experts to reach an agreement. However, the aim of this study was to gain a better insight into the different components and influences of current clinical practice, without the need for agreement. Therefore, focus groups set a perfect framework for discussion, including very different experiences and opinions from the different participants. Also, the discussion was considered to be enriched by the participants' various experiences. The results obtained show that foot orthoses prescriptions are variable and that there is no fixed process. Current clinical decision-making is integrated by an array of factors, which are mainly influenced by training and experience as well as patient expectations, however, when present, technology plays an insignificant role.

Practitioners base their clinical decisions mainly on their education and background. However, these habits change as they gain experience due to "trial and error". These variations on clinical procedures illustrate the influences that real patients have on their understanding of foot structure, biomechanics and orthotic principles, which can be viewed as an enhancement of the practice. They are also influenced by the type of patients they treat, which is defined by the different clinical suites they practice in. Furthermore, there is a large difference between the private and the public sectors, for instance, the time available for each patient and budget issues, among others. However, research has little impact on their clinical practice as it is often difficult to interpret and apply to day-to-day practice, so they continue with what is familiar to them.

Within this experience-based clinical practice, listening to the patient and history taking represents a fundamental part of the consultation. They invest time in listening to

the patient and the main aim of the treatment seems to have shifted towards reaching patient's expectations, often comprising biomechanical corrections. This diagnosis and prescription approach shifts away from the traditional goals of achieving biomechanical correction. It evidences the influence of experience over training, whereby practitioners attempt to achieve patient adherence to the treatment, as well as comply with the policies of the services they work in. This trend where practitioners change their clinical decision making based on their experience rather than their training has been referred to before (Jarvis *et al.*, 2012). Furthermore, other health care professions such as nursing show the same transitions, where students found big differences between what they learnt and what they observed in clinical practice (Kyrkjebo&Hage, 2005). This was endorsed by the discussion which made clear that the outcome they seek is the patients' perception of the treatment being successful, rather than biomechanical correction as defined in textbooks.

Discussions showed that in addition to orthotic prescription, practitioners referred to "counselling" and advising patients about wider issues such as activity and weight management, which also influence lower limb health. Informing patients about their disorder and how to improve it is also part of their role and has been shown to be an effective approach to enhancing the patient's adherence to the treatment and recovery (Ronnemaa *et al.*, 1997). However, practitioner knowledge of the success or failure of the treatment prescribed is determined by patient behaviour. Furthermore, they assume that patients are happy if they do not return to the clinic, and therefore, deem the treatment to be efficient and consequently, a success. However, this "non-return" by the patient can be influenced by many factors, such as a change in activity or medication, rather than a successful treatment. Moreover, it is common for patients to attend a different practice or to go to private practitioners when treatments are not effective (Malkin *et al.*, 2008). Accordingly, to avoid this lack of knowledge about the treatment effectiveness, some GP practices have started using patient's online access to their health records (de Lusignan *et al.*, 2014). This is one of the fields where technology could enhance clinical practice (Boonstra *et al.*, 2014).

Listening to the patient helps the practitioner reach a diagnosis and then to prescribe a treatment. Furthermore, during this prescription process, there are many factors to be considered by the practitioner. However, in the discussions, it remained clear that the simplest approach is taken initially. They agreed that most patients do not need

complex treatments and that standard insoles are effective for them. Also, it helps provide the patient with a treatment on the same day of the consultation, rather than having to book another appointment. This approach facilitates two of the main problems that practitioners have to face in their day-to-day practice, as well as low budget and time restrictions. Standard insoles are usually easier to fit in normal shoes which help with treatment adherence as patients are reticent to change their footwear to therapeutic shoes (Malkin *et al.*, 2008, Williams *et al.*, 2010, Williams&Graham, 2012). Often standard insoles fulfil both main goals of the treatment, which are patient happiness and biomechanical/symptom correction. However, this prescription habit contrasts with Australia and New Zealand, where the most popular insoles prescribed were customised (72% of the total insoles prescribed) (Landorf *et al.*, 2001).

In more complex cases, customised insoles have to be prescribed, particularly for patients with diabetes or rheumatoid arthritis. This approach entails insole design decisions to be made by the practitioner, such as casting technique or material choice. Regarding the choice of casting technique, foam box casting was the most popular approach agreed by practitioners during the discussion, because it is cheap, clean, fast and allows for correction of the foot position. In relation to materials, many factors including activity, BMI or underlying disease of the patient are considered. EVA was the most commonly used material by all participants in the focus groups. This is because it is cheap and easy to obtain, most practitioners have low budgets and their providers have a limited range of materials available. Also, EVA is very versatile as it can be obtained in different densities that comply with the different aims of treatments, such as accommodative in lower densities or motion control in harder ones. This material has been previously referred to as the most popular amongst practitioners in the NHS as well as in Australia and New Zealand (Landorf *et al.*, 2001, Malkin *et al.*, 2008). It is also easy to combine with other materials to enhance its effects depending on the treatment goal. It was agreed in the discussions that they knew how to combine different materials based on a "trial and error" approach and that they normally adhered to them rather than trying new materials reported in research publications.

Practitioners did not seem to follow research outcomes in general, not only regarding material innovations. Despite the general belief that published clinical guidelines are the best approach for clinical practice, the results obtained in this study

revealed that the influence of these guidelines on orthotic practice is limited. Practitioners agreed on experiencing difficulties in understanding and transferring research into day-to-day practice. This lack of use of guidelines and evidence-based practice seems to be shared by chiropractors in other countries such as Australia (Walker *et al.*, 2013). This reluctance towards guidelines tends to be based on the perception of these as "cookbooks" for clinical practice and podiatrists appear to have an "in my hands" mentality (Young, 2007). However, although other health care sectors base their clinical practice more on research outcomes than podiatrists (Young, 2007), there is still need to ensure that the evidence is relevant to the context in which it is being applied (Sandars&Heller, 2006).

A similar opinion was portrayed concerning the use of technology, where it was agreed that it was more research than clinical focused and has no place in day-to-day practice. One of the main issues that practitioners have is a lack of time per patient and they all agreed that technology is time-consuming to set up and calibrate to be worth using. Many of them stated that cupboards in their clinics were full of devices that were not used. They felt that currently available technology does not enhance their practice but replaces it, and they prefer having a feeling of ownership over their work. Also, devices give too many complex data, only a portion of which is actually used. Therefore, given the complex, time-consuming and costly reality of technology, it is not present in current orthotic practice despite the benefits it could provide. Consequently, there is a need to design technology according to the requirements and preferences of clinicians. This perception of technology differs from other health care professions, such as GPs, which find technology helpful and not time-consuming (Hayward *et al.*, 2015).

Despite not using technology in their practices, participants agreed that technology has the potential to enhance all aspects of orthotic practice. However, technology has to evolve and add value to clinical practice without adding to the burden of work. It was agreed in the discussions that the creation of templates that can be modified by the practitioner would speed up the process, adding certainty to design quality. These templates could also help to standardise the prescriptions within services and assess practitioners prescribing habits and outcomes. Also, the material characterization was discussed and it was agreed that it could enhance the combination of materials to achieve the treatment goals.

Evaluation of insoles before the patient leaves the clinic was another area identified where technology could help practitioners on a day-to-day basis. If treatments could be evaluated and tested for effectiveness on the same day of the consultation, it would help to avoid unnecessary appointments. It would allow the practitioner to make any corrections to the insoles before the patient commences the treatment and guarantees the success of the treatment as well as the happiness of the patient. Another matter that was agreed in the discussions was the possibility of "seeing" what happens inside the shoe when the patient is wearing the treatment. This information would improve their understanding of the way insoles work and would be able to identify potential issues more easily.

The need for further information for both practitioner and patient about the treatment outcomes was agreed. Aligned with this, practitioners stated that visual diagrams and representations of the treatment, including insoles, footwear and the way they work, would help the patient better understand why the treatment is necessary and how it works, thereby achieving better treatment adherence. Regarding what they, as professionals, would require from technology is a system to follow up the patient, with detailed information about how the treatment is working, how it is being used and the need for further appointments, therefore avoiding unnecessary appointments. This type of technology is being developed and adopted by some practitioners and trusts in the UK, where devices allow patients to evaluate their satisfaction while leaving the clinic (Wright *et al.*, 2016). Other approaches are mobile based with text messages or applications that allow the patients to inform their GP about their disorder state or check-ups (Bell *et al.*, 2012). Also, a platform that supports the practitioners' education, translating research outcomes into information applicable to clinical practice that can easily be made sense of and apply when necessary.

The need of clinically focused technology is an issue that clearly stood out during the discussions, which was agreed by all participants. There have been attempts by practitioners to integrate technology into their practice, but they all had negative experiences and led to the devices not being used. The reality in clinical practice is that time is limited per patient and technology should help speed up the diagnosis and prescription processes by giving clear, easy to understand data for both the practitioner and patient. It also should be easy to use and set up, with reliable data collection. There

are many new technologies for health care being developed to help practitioners in their day-to-day clinical practice. However, it seems that podiatry may not be one of their main profession targets.

4.6.1 Conclusion

The results obtained in this study show that clinical orthotic practice is mainly based on training and experience, with the variations between practitioners reflecting the integration of education with local factors. Decision making for a prescription involves a combination of the patient's needs and expectations, as well as the correction aims from the practitioner. Interestingly, the influence of research and evidence-based guidelines on their diagnosis and prescription habits is limited. Technology is mainly absent, being described as too complex and time-consuming. Measuring outcomes from their practice is significant for practitioners, but there are no current means of achieving this. This investigation has provided a novel insight into clinical orthotic practice, but further research is needed to obtain a broader understanding of the different factors that influence clinical practice.

Practitioners agreed that they did not generally follow research outcomes and general guidelines. This was surprising as the literature is considered as the main resource for practitioners to find out about new treatments or materials to use. Moreover, rather than basing their clinical practice on the literature or their training, it is based on their experience the demands of patients. This finding on its own is not surprising, but it shifts the decision making from theory to patient expectations. The clinicians' practice appears to change with experience, becoming a more personal interaction with the patients in an attempt to fulfil their expectations and often comprising biomechanical aims.

4.6.2 Limitations

An important limitation of this study is that all the participants were selected from health services in the UK which could affect the extrapolation of the results to other health care professionals and other care settings. However, the participants were selected based on their broad clinical experience, as well as their knowledge of other practitioners within their own services and networks. Furthermore, the main objective of this study was to gain a better insight into current orthotic practices from a personal and professional

perspective, which was the reason to select experts on the provision of insoles. However, this study was the first step in understanding the variations and factors that influence clinical practice, consequently, the results are limited. There is still a lack of information about the provision of insoles, including how it may vary among all the professional groups involved in orthotic design and manufacture. Hence, further research is needed to have a more in-depth understanding of the different factors that influence clinical orthotic practice.

5 Overview of experimental data collection and insole design process

Three separate studies were designed to address the research questions defined at the end of Chapter 3. For the three quantitative studies, a single group of 60 patients with diabetes and peripheral neuropathy were recruited and visited the laboratory on a number of occasions (see details below). This chapter provides details of all the processes common to all three quantitative studies, such as participant recruitment and data collection. A full detailed description of each experimental data collection and processing is presented subsequently in the corresponding chapter. This chapter also describes the design process for the insoles tested in this PhD thesis.

5.1 Overview of recruitment and experimental testing for the quantitative studies (2-4)

5.1.1 Inclusion and exclusion criteria

People with diabetes mellitus (DM) and peripheral neuropathy were recruited for studies 2-4 who fulfilled the following criteria:

- Inclusion criteria
    - > 18 years of age
    - diagnosed with DM
    - diagnosed with neuropathy
    - be able to travel to the University of Salford on three different occasions
    - be able to walk for 1.5-2 hours
    - be able to understand both written and spoken English
- Exclusion criteria
    - any partial or full foot amputation
    - a major foot deformity sufficient to limit activity or prevent the wearing of off-the-shelf shoes
    - any skin condition which could be affected by adhesive marker tape

- suffer from any disorder which affects balance or mobility and/or a history of falls, or walk with stick or clutches
- lack of joint mobility (which may make them unsuitable for our insole designs)
- previous history of ulceration

These exclusion criteria positioned our subjects as medium-risk within the UK NICE guidelines for the assessment and foot risk classification of patients with diabetes (NICE, 2016). According to these, the presence of neuropathy is a risk factor, but the absence of previous ulceration makes them not high-risk locating them on the medium-risk group.

5.1.2 Approaches to recruitment

Two different methods were used to recruit participants, recruitment through local GPs and via radio advertisement. Ethical approval was sought from the NHS ethics committee and obtained in September 2013 (REC number 13/NW/0331). Following NHS ethics approval, adoption from the NHS portfolio was requested.

The Global Company was contacted to arrange a radio advert. Considering the target population needed for the study, they recommended running the advert (see the script in Appendix 8) with Capital FM and Gold Manchester. The advert was aired for the first time in January 2014, continuing for four weeks. People interested in taking part in the study sent text messages to the number provided in the advert, and the radio company forwarded their phone numbers. A total of 350 people showed interest in the study. They were phoned by the researchers and underwent a phone screening questionnaire (see Appendix 9). Following this questionnaire, a total of 30 subjects were deemed suitable for the study. Accordingly, and following NHS ethics requirements, a podiatrist was sent to their homes with their permission, to perform a neuropathy screening to confirm their suitability to take part in the study. Only those who showed signs of neuropathy were invited to the University to take part in the study. A total of 14 eligible participants out of the 30 subjects screened on the phone were deemed suitable (Figure 5.1) and were booked in for an appointment at the University for the first visit data collection.

A total of eight different GPs made contact to help with recruitment. The inclusion/exclusion criteria were sent to each practitioner to enable them to perform an electronic database search. All potential eligible participants were then contacted by post and provided with a letter of invitation and a participant information sheet (see Appendices 6&7). Those interested in participating in the study were asked to make contact with the research team. A total of 1190 letters were sent to patients, of which 98 made contact. To ensure that no ineligible participants were invited, each person who responded was asked some simple questions (see the document in Appendix 9) over the phone. Those who appeared to satisfy the criteria (n = 48) and were happy to participate after better understanding what the testing entailed, were subsequently visited by a podiatrist at their own home for a complete neuropathic screening. All participants deemed neuropathic after this screening (n = 46) were invited to participate in the study (see Figure 5.1).

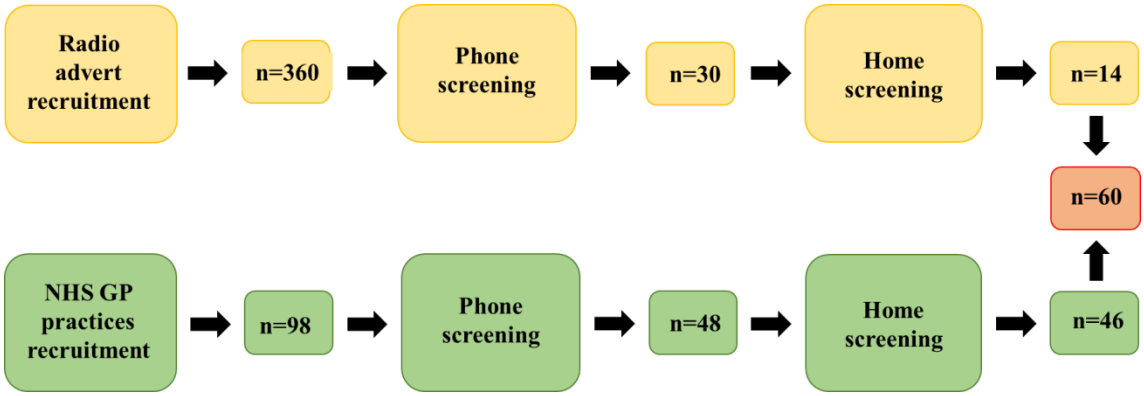

Figure 5.1: Recruitment process

A total of 60 participants satisfied the inclusion/exclusion criteria and were recruited. The participants included 40 males and 20 females, with a mean age of 65.9 ± 12.6 years, ranging from 25 to 87 years old. They were overweight to obese, with a mean body mass index (BMI) of 29.41 ± 5.2 kg/m^2. This sample was representative of patients with diabetes and neuropathy, who are normally of old age, overweight, and more commonly men (Zimmet, 2014). Each participant visited the laboratory on at least two occasions (first visit and second visit), see Figure 5.2 below. During the first visit, a range of different variables (biomechanical, clinical and demographic) were measured. These data were used to design the nine insoles (described in Section 5.2.3) which were subsequently tested (plantar pressure measurement) during the second visit. Also, a total

of eight subjects (from the original 60) attended for testing on a third occasion. During this third visit, plantar pressure data collection protocol from visit two was repeated to address the first research question relating to reproducibility.

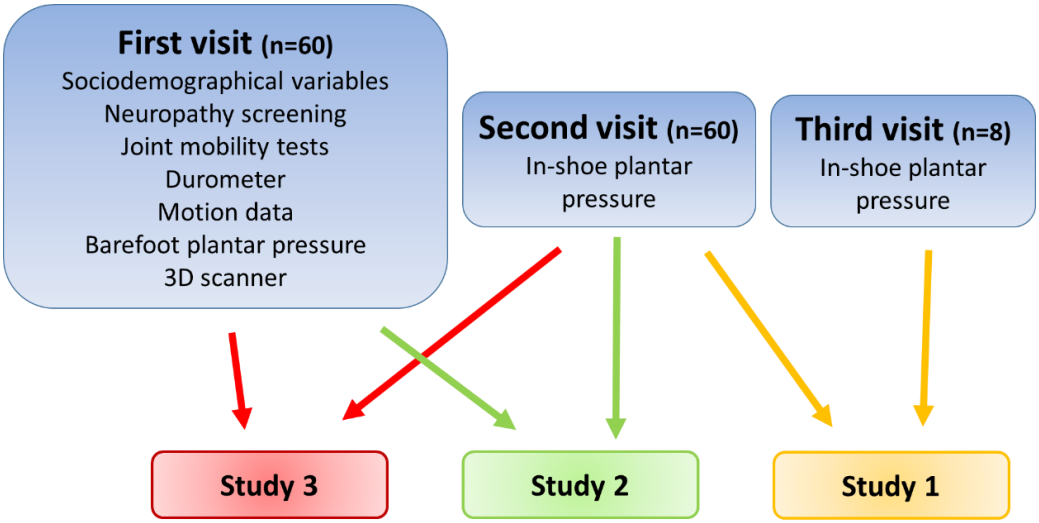

Figure 5.2: Overview of the tests performed during the study visits

5.1.3 Data collection visit 1

All participants underwent a neuropathy screening, in a lying position, to confirm their suitability to participate in the study. Light touch and vibration sensibility were tested using a monofilament and a tuning fork. In addition, subjective symptoms were recorded using the Diabetic Neuropathy Symptom Score. These screening tests were chosen because they are commonly used in day-to-day clinical practice to test neuropathy (Dixit, 2014). Once subjects were confirmed as suitable, they read the information sheet and were invited to ask questions, after which they provided informed consent to participate by signing the consent form. Socio-demographical variables were then recorded, including gender, date of birth and height, weight and BMI.

5.1.3.1 10 g Semmes-Weinstein Monofilament

Light touch sensitivity loss was assessed using a 10 g Semmes-Weinstein monofilament. Nylon monofilaments are constructed to buckle when a 10 g force is applied and loss of ability to detect pressure at the point of buckling, at one or more anatomic sites on the plantar surface of the foot, has been associated with loss of large-

fibre nerve function (Boulton *et al.*, 2008). This approach is common practice and has been used in a number of prospective studies which have reported that loss of pressure sensation is highly predictive of subsequent ulceration (Boulton, 2010, Dixit&Maiya, 2014). Moreover, it has also been shown to be highly reproducible (85%) (Tan, 2010) when compared with pulse palpation. Several studies report using the monofilament on only four different sites of the forefoot, and test being positive when one or more of these was not felt. Currently, there is no consensus on the protocol for the use of the monofilament with regard to the location and number of test sites, as well as the number of insensate sites to be classified as the presence of neuropathy. Testing 10 sites (Figure 5.3) evaluates all dermatomes of the foot and may improve the sensitivity and specificity compared with testing 4 sites (Singh *et al.*, 2005).

In this study 10 different sites on the foot were tested in random order: 1st, 3rd and 5th toes, 1st, 3rd and 5th metatarsal heads, internal arch, external arch, heel and dorsum between 1st and 2nd toes (Figure 5.3). Participants were asked to close their eyes and identify the site that the monofilament was being applied to. Areas of hard skin were avoided as it was felt that they might bias the result of the test. The test was taken to be positive for neuropathy if the patient could not feel the monofilament at one or more sites (Feng *et al.*, 2011). The approach taken in this study was more conservative including the rear foot and the test considered positive when one or more of these was not felt.

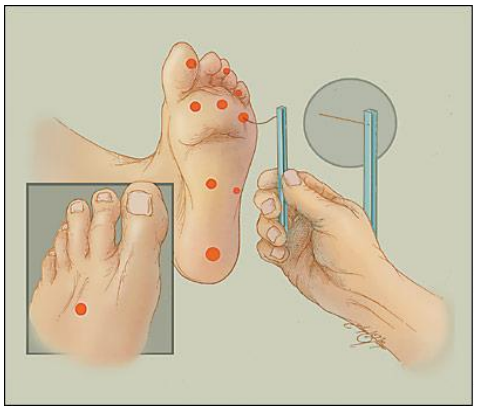

Figure 5.3: Monofilament test areas

5.1.3.2 128 Hz tuning fork

A 128 Hz tuning fork was used in order to test vibration sensitivity as it has been shown to be sensitive to neuropathy (Al-Geffari, 2012). It has been found that an inability

to sense vibration at different sites is clinically indicative of peripheral neuropathy (Takahara *et al.*, 2014). Furthermore, in combination with the monofilament, it has been shown to be a good predictor of patients who later developed foot ulceration (Feng, 2011).

The tuning fork was applied to bony prominences bilaterally: internal and external malleoli and 1st and 5th metatarsal heads (Al-Geffari, 2012). The participant had their eyes closed throughout and they were asked to indicate when they could sense the vibration. The test was considered positive for neuropathy when one or more of the vibrations could not be sensed (Dixit&Maiya, 2014).

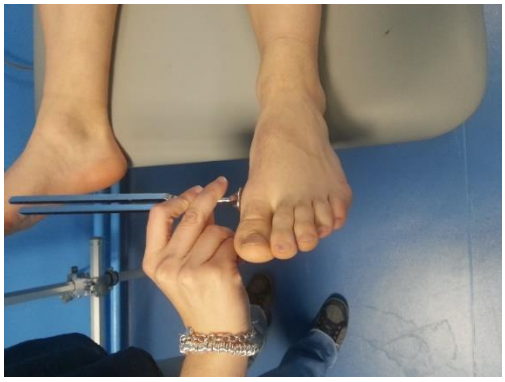

Figure 5.4: Example of tuning fork test on the 1st MPJ

5.1.3.3 Diabetic Neuropathy Symptom Score

The Diabetic Neuropathy Symptom Score was used to assess the subjective symptoms of neuropathy, which are important as they reflect the complaints of the patient and may be of additional diagnostic or prognostic value. Although several scores have been developed to assess symptoms of diabetic neuropathy, such as the Neuropathy Symptom Profile, the Michigan Neuropathy Screening Instrument (MNSI) and the modified NSS scores of Veves and Young (Dyck *et al.*, 1986, Veves *et al.*, 1993, Young *et al.*, 1993, Feldman *et al.*, 1994), the Neuropathy Symptom Score has been widely studied and accepted as valid and sensitive to detect neuropathy (Meijer *et al.*, 2002). The Diabetic Neuropathy Symptom Score tests the following areas: unsteadiness in walking, pain, burning or aching in legs or feet, prickling sensations in legs or feet, and numbness in legs or feet. The presence is scored 1 and absence 0, with the presence of any symptoms in any of the areas considered indicative of neuropathy.

At least two of the screening tests described above had to be positive for a definite diagnosis of neuropathy. Once the diagnosis of neuropathy had been confirmed, and the

participant deemed eligible for the study, a range of further measurements were taken (see Table 5.1) to provide the biomechanical and clinical variables required to address Study 3 (Chapter 8) and also to produce the manufacturing specification for the different insole designs tested in Study 2 (Chapter 7). Table 5.1 provides a reference to the subsequent section in which the tests are described in more detail and the chapter presenting the data.

Measurement	Study/Insole design	Chapter Number
Socio-demographical variables	3	8
Characterisation of foot segment lengths	3	8
Skin stiffness characterization	3	8
Joint mobility (ankle, subtalar, and 1st MPJ)	3	8
Lower limb motion	3	8
3D foot scan	Insole design only	5
Barefoot standing plantar pressure	Insole design only	5

Table 5.1: Different data sets collected on day one and details of study used in and where it is within this thesis

5.1.4 Data collection during visit 2 and 3

All participants returned for a second visit approximately 4-5 weeks after their initial visit. During this intervening period, customised insoles were manufactured for each participant, a process which is explained in more detail in Section 5.2.3. During the second visit in-shoe pressure data was collected while participants walked in a standard Oxford shoe for males and wedged shoe for females (Figure 5.5) using each of the nine separate insole designs. Further details on these pressure testing measurements are provided in Chapter 6.

Standard shoes with a removable insole were used to test the insole conditions designed for the different studies presented in this thesis. It was decided to not use orthopaedic shoes because the participants had no significant deformities or history of amputation. In addition, such participants tend to be reluctant to change their normal footwear for aesthetic reasons (Williams *et al.*, 2007, Williams *et al.*, 2010). Accordingly, one of the study aims was to investigate the PP reduction that could be achieved with

fully customised insoles, based on technology, with a standard shoe. For males, an Oxford shoe with laces (Figure 5.5) was chosen as this style is a popular choice among most men, as well as being an appropriate type of shoe for these patients. For females, a wedged Mary Jane shoe with a buckled strap and a lycra forefoot was selected (Figure 5.5) as it provides enough room to fit the insole and the foot comfortably, as well as being aesthetically appealing for women. Also, the buckled strap allowed the shoe to be fastened and adapted to the individual foot shape and size. The main difference between the male and female shoes was the pitch. However, the female shoe had a platform under the forefoot which made the heel pitch smaller than it appeared and only 1.5 cm greater than the male shoe. Recent research (Melvin, 2014) has shown that heel pitch only has a significant effect on PP when it is higher than 3.5 cm. Therefore, the difference in pitch between the male and female shoes is unlikely to have affected the findings presented in this thesis.

To address the research question relating to repeatability a total of 8 participants returned to the laboratory for a third visit, typically 3-5 weeks after their second visit, during which the in-shoe pressure measurement protocol, outlined above, was repeated.

Figure 5.5: Standard shoes used with the customised insoles for in-shoe pressure measurement

5.2 Customised Insole designs for studies 2-4

Previous research has shown that customised insoles with a standard metatarsal bar (i.e. same design for all patients) can effectively offload plantar pressures from the forefoot of people with diabetes (Mueller *et al.*, 2006, Guldemond *et al.*, 2007). There

has been only one study by Owings *et al*. (2008) which has evaluated the benefits of a customised metatarsal bar shape in a fully customised insole, using plantar pressure distribution to determine metatarsal bar shape and location. However, this study did not investigate optimal proximal/distal placement of the metatarsal bar in relation to the location of pressure, choosing only to place the bar immediately proximal to the areas of highest pressure. Furthermore, they did not explore the effect of different cushioning materials used under the area of highest pressure, just distal to the custom metatarsal bar.

Studies 3 and 4 (Chapters 7 & 8) were designed to address this limitation by testing the effect on peak pressure of different metatarsal bar locations relative to peak pressure data and different materials distal to the bar. All the insoles tested as part of this work were individually designed and manufactured using computer-aided design and manufacture (CAD-CAM) technologies to ensure accuracy in the design and manufacturing process. The inputs to the CAD-CAM process were 3D foot shape and a barefoot plantar pressure profile collected during standing. These data were used in the CAD software to produce a digital geometric model of each insole which was then sent to a CAM software-driven milling station that milled the insoles from an EVA block. The following sections document this design process in more detail.

5.2.1 Capturing foot shape information

The precise individual foot shape was obtained using a 3D scanner during the first visit. This scanner incorporated four separate 2D cameras and had a total scanning volume inside the scanner of 81 dm^3, external dimensions of 420 x 160 x 120 mm and shape capture accuracy of +/- 1 mm. The scanner has a platform around it that allows the subject to stand in a normal comfortable position while placing one foot inside the scanner and the other outside (Figure 5.5). For this test, the subject was asked to stand normally, with one foot inside the scanner and the other foot on the platform, with their weight distributed equally between their two feet. This process was repeated for each foot.

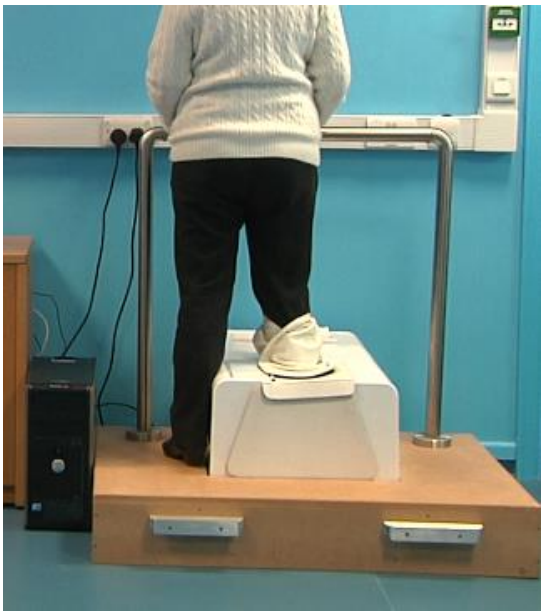

Figure 5.6: Subject in a normal standing position

Once data capture was complete, the scanner software integrated the data recorded from each of the 2D cameras, creating a 3D image from hundreds of data points forming a point cloud. From this point cloud file, the software created a solid 3D image of the foot by connecting all the data points with a continuous surface (see Figure 5.7). This solid mesh file was saved and then imported into the CAD software used to design the insoles.

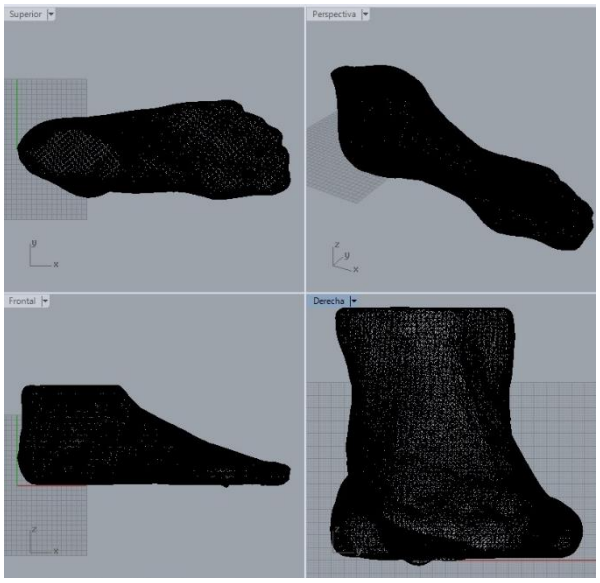

Figure 5.7: 3D foot shape taken from the 3D scanner

5.2.2 Recording the static plantar pressure map

The Barefoot plantar pressure during standing was collected during the first visit using an Emed® pedography platform, an electronic system for recording and evaluating pressure distribution under the foot. The technical specification of the platform is given in the table below:

Platform size: 700 x 403 mm²	Sensor area: 475 x 320 mm²
Number of sensors: 6,080	Sensor resolution: 4 sensors/cm²
Measuring range: 10 - 1,270 KPa	Maximum total force: 193,000 N
Recording frequency: 50 Hz	Accuracy: ± 5 % ZAS

Table 5.2: Technical specifications of the Novel Emed platform

The pressure platform was embedded in an 8 m EVA mat, which had the same thickness as the platform to ensure a consistent height surface, therefore, allowing the subject to stand normally (Figure 5.8). Participants were asked to stand placing only one foot at a time on the platform, with the other one on the EVA mat and to keep their weight equally distributed between their two feet. Data was then collected for 5 seconds and the Novel Emed software calculated the peak pressures.

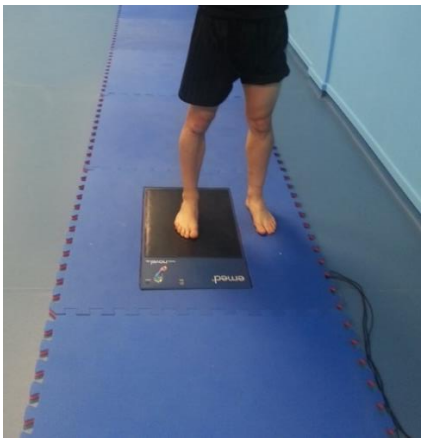

Figure 5.8: Emed platform layout

5.2.3 Insole design process

Following the measurement of foot shape and static pressure during the first visit, 9 pairs of customised insoles were manufactured for each subject. These allowed for the three bar locations (proximal, middle, distal) and three material options in each location (Poron, EVA, void).

The design process was performed using a plug-in for the Rhinoceros software (Robert McNeel & Associates, USA) in the five stages below:

1. creation of a customised insole from the 3D foot shape data
2. overlay of the static pressure map onto the 3D foot shape data
3. location the plantar pressure data points which define the position of the metatarsal bar and the void in the insole
4. projection of the defining points onto the customised insole and creation of the customised base metatarsal bar and void
5. adjustment of the metatarsal bar and void positions to allow for the 9 variations in insole design.

5.2.3.1 Step 1: Creation of a customised insole from the 3D foot shape data

The 3D foot shape was imported into the CAD software, which then identified the insole whose length would best fit the foot from a range of standard insoles (based on Salfordinsole geometries). Once this insole template was loaded, it was then customised by adapting the curves that defined the top surface of the insole to the plantar aspect of the foot mesh (Figure 5.9). The foot shape determined the orthotic shape up to the end of the medial arch, and after that, the insole was flat. The insole was modified to be 5 mm thick under the forefoot to accommodate the 3 mm deep void that would be added later (described in Step 5).

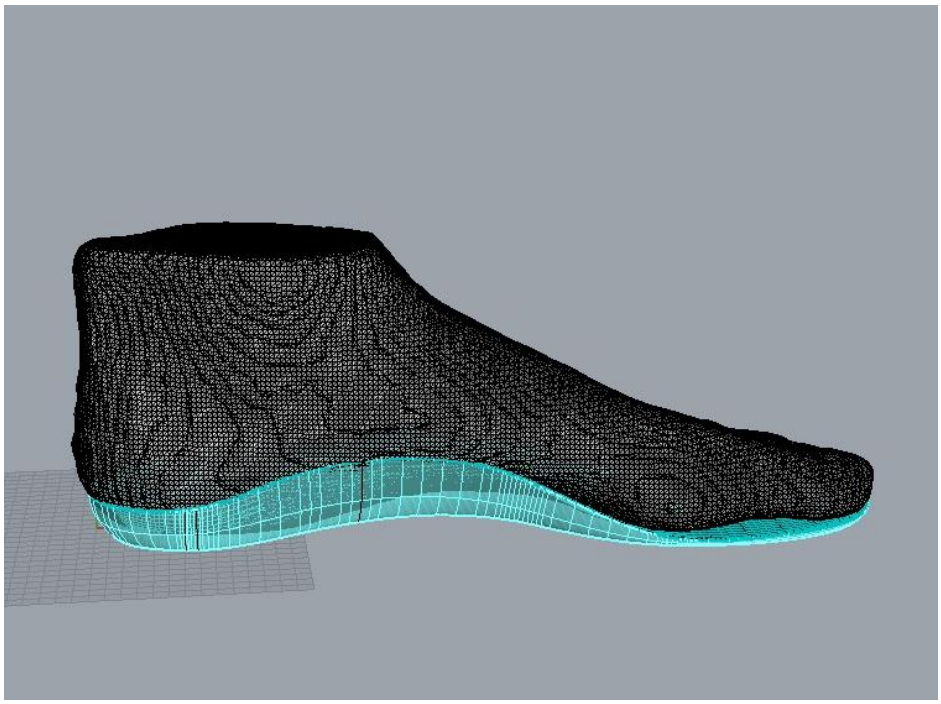

Figure 5.9: Insole customization from the 3D image of a foot

5.2.3.2 Step 2: Overlay of the static pressure map onto the 3D foot shape data

The position of the metatarsal bar and void, and thus, the location of the cushioning materials, Poron and EVA, was dictated by the plantar pressure distribution which was required to align with 3D foot shape and orthotic shape data. The pressure data was first mapped onto the 3D foot shape data and then, the position of the bar and void was specified from this pressure map. A bespoke Rhinoceros plug-in, specially developed to accurately match the pressure map file and the foot shape file (Foot Pressure Viewer, developed in European Union project SSHOES), was used to position the static pressure map over the 3D foot shape. This allows a designer to understand the relationship between foot shape and plantar pressure location (Figure 5.10).

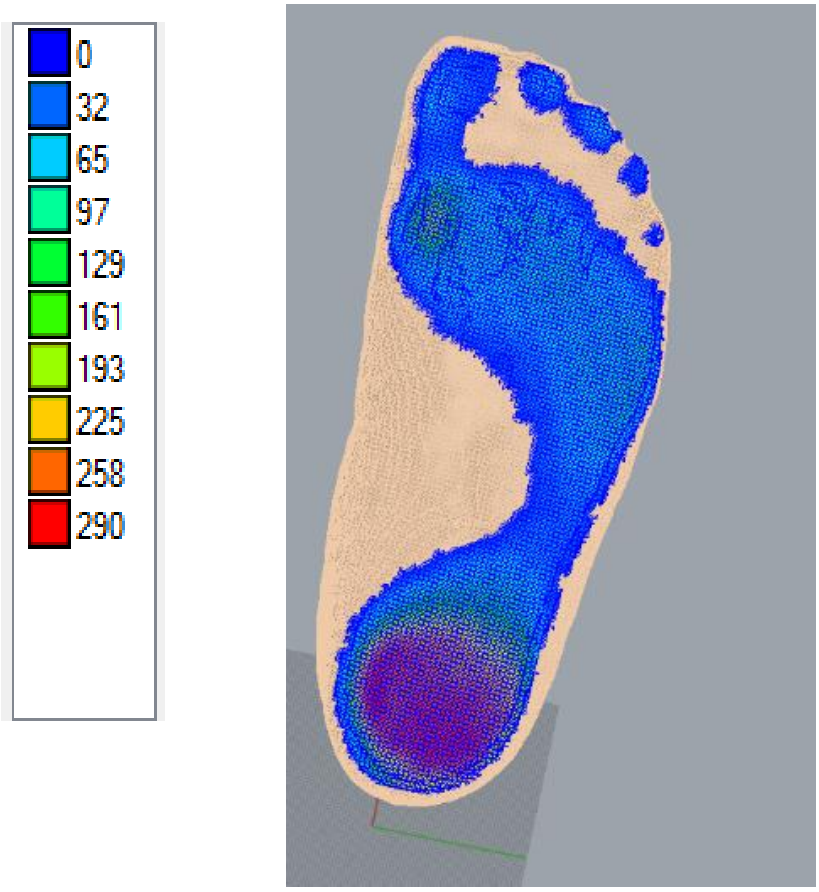

Figure 5.10: 3D foot shape and plantar pressure map aligned using a Foot Pressure Viewer with the colour scale based on pressures (KPa)

5.2.3.3 Step 3: Define the position of the metatarsal bar and the void

Once the static pressure map was aligned with the 3D foot shape data, the position of the metatarsal bar and the void space for the base insole design were defined.

Metatarsal bar design: To standardise the pressure maps, each subject's data was normalised such that the maximum pressure was 300 KPa, to ensure consistency of the colour maps between participants (Figure 5.11). A medial-lateral line was then defined by 5 points proximal to the peak pressures, where the pressure was 77% of the peak pressure. On the regions where peak pressures were lower than 77% of peak pressures, the points were located in the 33% value of peak pressure (Figure 5.11). This line defined the proximal border of the void and the distal border of the metatarsal bar and is referred to as the metatarsal bar defining line in Figure below.

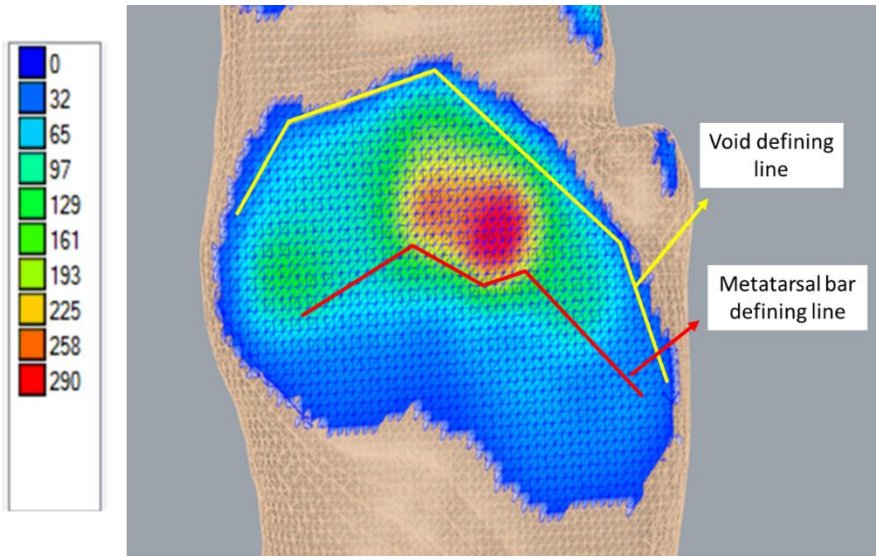

Figure 5.11: Design of the five defining points for the metatarsal bar and void

Void design: Once the metatarsal bar defining line had been specified, a further 5 points were used to define the distal border of the void. These 5 points were located at the point where the pressure dropped below 10% of the peak pressure, as shown in Figure 5.12. The two lines (void defining line and the metatarsal line) are shown in Figure 5.12 above and defined the void region.

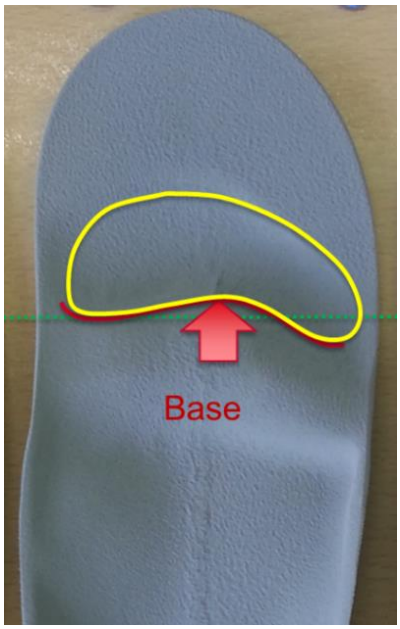

Figure 5.12: Void design and position

5.2.3.4 Step 4: Projection of the defining points onto the customised insole and creation of the base metatarsal bar and void

The CAD software loaded a standard metatarsal bar onto the customised insole created in Step 1. The distal edge of this bar was then customised in shape to match the metatarsal bar defining line and the metatarsal bar line (Figure 5.12) was projected from the foot shape onto the insole. This line was then used to define the distal border of the metatarsal bar. All metatarsal bars were designed with a maximum height 2% of the foot length, for example, a participant with a size 7 had a bar of height 5 mm = 0.02 x 250 mm (size 7).

The void defining line (Figure 5.13) was then projected onto the insole so that the geometry of the void space could be defined. As explained above, the void was situated directly distal to the metatarsal bar with a distal boundary corresponding to the void defining line. The depth of the void was set at 3 mm for all participants.

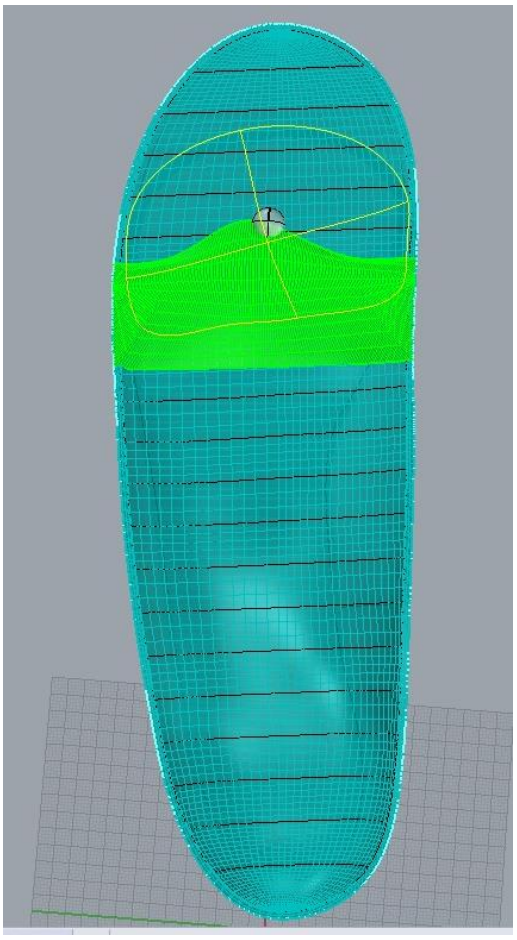

Figure 5.13: Void design

5.2.3.5 Step 5: Definition of variations in the metatarsal bar and void positions

Once the baseline design of the metatarsal bar and void was completed, two further designs were created by moving the metatarsal bar proximally and distally by 2% of the foot length. This percentage was chosen as it corresponds to a distance of 5 mm on a size 7 insole and 5 mm is a typical distance used in previous studies of metatarsal bars (Hayda *et al.*, 1994). In the proximal and distal designs, the line defining the distal boundary of the void was kept constant and the proximal line defining the void adjusted accordingly in the CAD software. This resulted in a large void for the proximal designs and a small void for the distal designs.

5.2.3.6 Manufacture

CAM and direct milling of EVA blocks in the manufacturing process ensured accurate recreations of the insoles being tested. Insoles were manufactured by Todo Para Sus Pies S.L. (TPSP), a Spanish company specialising in customised shoes and insoles. Insoles were made of medium density EVA (50º Shore A) and manufactured with CAM software, which imported the insole files into a milling machine.

The idea was to use a different cushioning material in this void region. However, to minimise costs and the need to produce a large number of different insoles, it was decided to create a cutout, with a depth of 3 mm, in which different materials inserts could be placed, as shown in Figure 5.14. With this approach, one insole was used with three insert options (Poron, EVA & empty void). Two different cushioning materials (3 mm Poron and 3 mm low-density EVA) were used to fill the void and form two of the three material conditions (the third being an empty void). These are two of the most common materials used by podiatrists when designing insoles for patients with DM (Fauli *et al.*, 2008). Each material insert was manually cut to match the shape of the void on a patient by patient basis.

The design and manufacture process above created nine different pairs of insoles for each participant, which were then combined with the flat insole that came with the shoe to produce a total of ten different conditions (Table 5.3):

	Condition	Metatarsal bar position	Forefoot material
1	D + EVA	Base metatarsal +2% of foot length	Soft EVA
2	B + EVA	Base metatarsal line	Soft EVA
3	P + EVA	Base metatarsal -2% of foot length	Soft EVA
4	D + Poron	Base metatarsal +2% of foot length	Poron
5	B + Poron	Base metatarsal line	Poron
6	P + Poron	Base metatarsal -2% of foot length	Poron
7	D + Void	Base metatarsal +2% of foot length	Void
8	B + Void	Base metatarsal line	Void
9	P + Void	Base metatarsal -2% of foot length	Void
10	Sshoe	Flat insole condition	-

Table 5.3: The ten different insoles conditions used in this study. P: proximal metatarsal bar; B: base metatarsal bar; D: distal metatarsal bar; SShoe: standard shoe

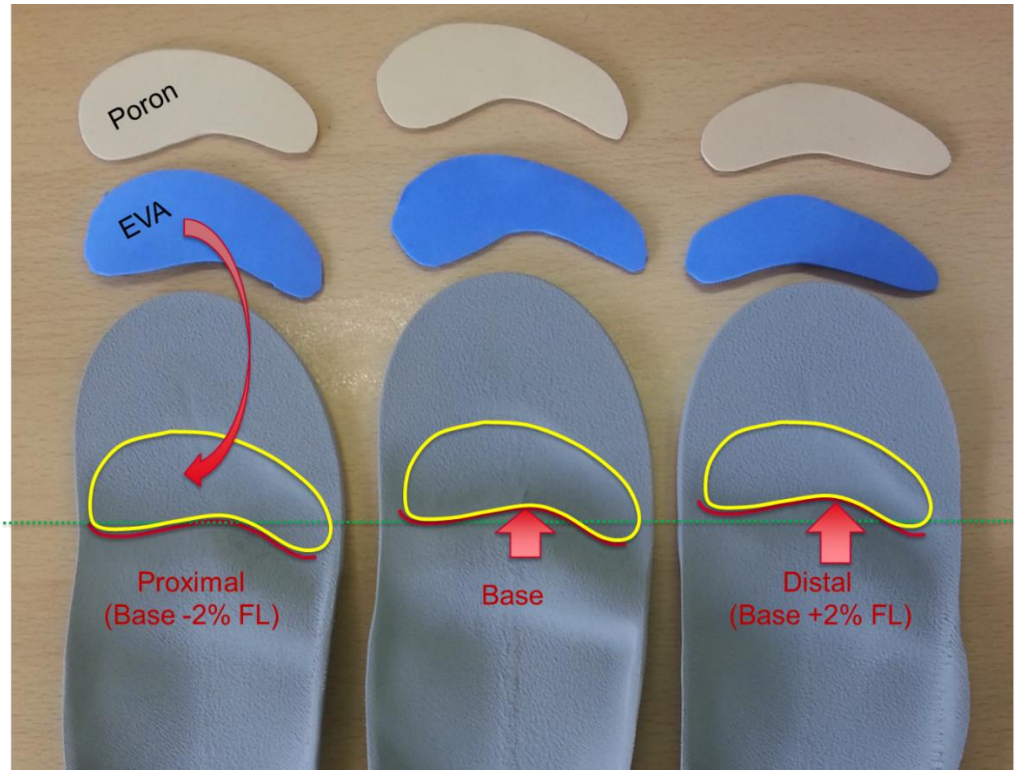

Figure 5.14: The different insoles used for the study with different cushioning materials

6 Reproducibility of plantar pressure collection using a wireless in-shoe pressure device

6.1 Background

One of the key objectives of this thesis is to understand the effect of different design features of a fully customised insole on plantar pressures in people with diabetes and neuropathy. To develop this understanding, it is necessary to quantify pressure offloading across a range of different insole designs and from these data, identify the best performing insole design. However, this approach requires plantar pressure measurement which is both precise and repeatable. Repeated measurements of physiological/biomechanical variables, such as plantar pressures, are associated with some variability. This variability can arise from variability in an individual's capacity to repeat a given task as well as from errors/variability in the measurement processor, the circumstances under which the measurements take place (de Vet *et al.*, 2006). Therefore, to be able to interpret correctly the results of subsequent chapters which examine the effects of different insole designs, it is necessary to have a clear understanding of the level of reproducibility of plantar pressure measurement in people with diabetes and peripheral neuropathy.

There are two main approaches to quantifying reproducibility referred to as agreement and reliability (de Vet *et al.*, 2006). Agreement and reliability parameters focus on two different questions:

1. ''How good is the agreement between repeated measurements?'' This concerns the measurement error and assesses exactly how close the scores for repeated measurements are.

2. ''How reliable is the measurement?'' which characterises how well patients can be distinguished from each other despite measurement errors.

Reliability is the extent to which measurements can differentiate between patients, despite any measurement errors that may influence measured values. In contrast, agreement defines how close repeated measurements are to one another and is quantified in the actual unit of the measurement (de Vet *et al.*, 2006).

The calculation of the Standard Error of Measurement (SEM) is based on the measurement from a single subject taken an infinite number of times. In this scenario, each of the individual measurements would be slightly different because of measurement error. However, the distribution of these measurements can be described by a normal distribution and will be observed to cluster around a 'true' mean value with a variability characterised by a within-subject standard deviation. The more reliable the measurement response, the less variability and so the smaller the within-subject standard deviation (Bruton, 2000). The SEM is calculated by averaging the spread of measurements for each individual across the whole group. This calculation takes into consideration the possibility that some of the observed change may be due to random measurement error. Therefore, it can be used to define the difference needed between separate measures on a subject for the difference in the measures to be considered real (Weir, 2005).

The Intraclass Correlation Coefficient (ICC) is used to quantify reliability by relating the measurement error to the variability between individuals in the population under study. It is defined as the ratio between the variability from true differences in the measured variable between individuals and the total variability, which is the sum of the true variability and the measurement error. Therefore, the ICC does not just reflect the measurement error but also the characteristics of the sample chosen. Consequently, the results have to be interpreted regarding the sample used. For example, it would be inappropriate to calculate the ICC from measurements on a group of healthy individuals (which is common in the literature because it is generally easier) and then apply the results to a particular patient group (Baker, 2013). An early paper suggested that values of the ICC as low as 0.6 should be regarded as indicating 'substantial' agreement and over 0.8 as 'almost perfect'(Landis&Koch, 1977). More recent reports are less generous suggesting that 'for many clinical measurements, reliability should exceed 0.9 to ensure reasonable validity' (Portney, 2009).

Reproducibility of in-shoe plantar pressure collection has been previously studied by some authors who have demonstrated high agreement and reliability (Ramanathan *et al.*, 2010, Sawacha, 2013, de Castro *et al.*, 2014). These studies have used the most popular in-shoe devices, Novel Pedar, Walkinsense and F-Scan, with the Novel Pedar system regarded as having the best reproducibility. Amongst the studies testing Novel Pedar reproducibility, all reported good results in healthy subjects while wearing standard shoes with no insole inside (Murphy *et al.*, 2005, Putti *et al.*, 2007, Ramanathan *et al.*, 2010). However, these findings may not extrapolate to patients with diabetes and neuropathy who often use complex contoured insoles. This patient group are likely to have impairments in balance associated with their neuropathy (Allet *et al.*, 2008) which may affect cadence and foot biomechanics leading to inconsistent gait patterns (Allet *et al.*, 2008).

Another limitation of previous studies investigating the reproducibility of plantar pressure data is that they have tended to focus on flat insoles (Putti *et al.*, 2007, Ramanathan *et al.*, 2010). It is therefore not clear whether similar levels of repeatability would be observed with contoured insoles, especially if worn by people with diabetes and neuropathy. Accordingly, the aim of this study was to develop a precise understanding of the agreement and reliability of pressure data collected from customised insoles in people with diabetes and peripheral neuropathy.

6.2 Study design

To investigate the reproducibility of plantar pressure collection, pressure data was collected on two separate occasions from eight individuals with diabetes and peripheral neuropathy. For each participant, a total of nine different insole designs (Chapter 5) were tested along with a standard contoured control insole in a controlled laboratory environment. The data from the two sessions were compared using SEM and ICC to quantify reproducibility.

6.3 Data collection

A total of 8 participants with diabetes mellitus and peripheral neuropathy were required to visit the Human Performance Laboratory located at Brian Blatchford Building at the University of Salford on two separate occasions. On both visits, plantar pressures

were collected using Novel Pedar in-shoe pressure device while wearing standard shoes and different fully customised insoles. The same speed and walking conditions were applied on both occasions, and the same shoes and insoles were used.

6.4 Plantar pressure measurements

Novel Pedar insoles were used to collect in-shoe plantar pressure data. This system was chosen as it has been shown to be the most reproducible device for plantar pressure collection during dynamic activities (de Castro *et al.*, 2014). The Pedar insoles have a matrix of sensors arranged in rows and columns which enable monitoring of the entire plantar area of the foot during walking. The insoles are made of capacitive sensors with elasticity to conform well to the three-dimensional surface of the orthotics. These sensor insoles are connected by cable to body-mounted transmitter box which sends the data to a computer via Bluetooth® telemetry. These data can then be observed in real-time on the computer screen.

For the data collection, all the nine insoles designed for each participant (Chapter 5) were tested in a standard oxford shoe for males and wedged shoe for females (Figure 6.1). This shoe has an internal insole that could be removed to allow the customised insoles to be accommodated within the shoe. In addition to the nine different customised insoles (Figure 6.2), data from a standard insole was also collected and set as the control condition (Figure 6.3), meaning that a total of ten conditions were tested on each subject. For each one of the conditions, the participant was asked to along a 20 m walkway at their self-selected speed. This speed was determined with the control insole and measured using optical timing gates. For the following trials, speed was monitored using optical timing gates and only trials within ±10% of normal speed were considered acceptable, however, trials within ±5% of average speed were selected when possible. A total of 18-25 steps were collected from each walk, with a minimum of five walks at the correct speed, giving approximately 100 steps per insole condition.

Figure 6.1: Standard shoes used for testing

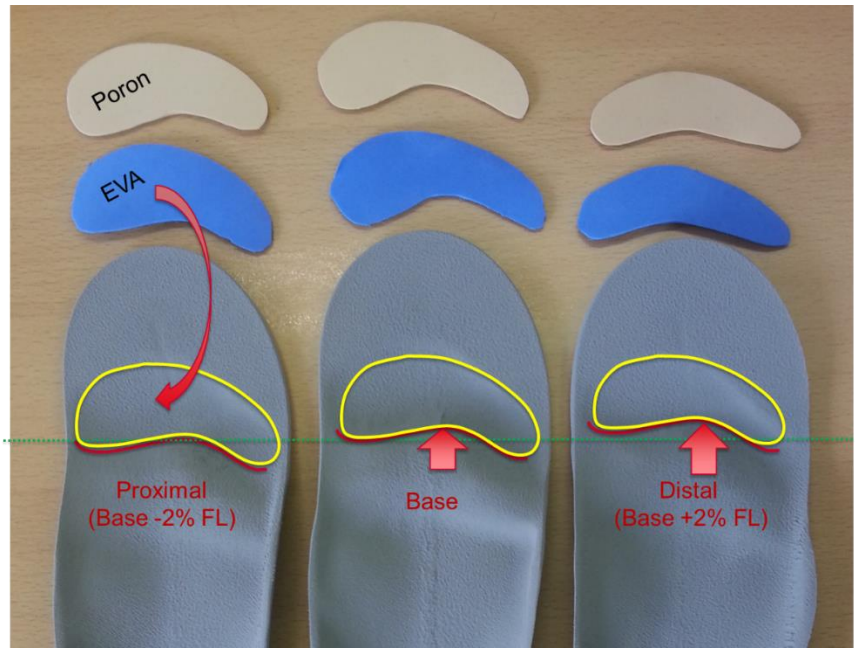

Figure 6.2: Different insole conditions used

Figure 6.3: Standard insole set as the control

Each of the eight participants returned to the laboratory for repeat testing approximately one month (between 3-5 weeks) after the initial test. This repeated testing

followed the same protocol as the initial testing with the same set of ten insoles and the same walking speed. Again, speed was monitored using optical timing gates and only trials with 5% of the target speed considered acceptable.

6.5 Data analysis

6.5.1 In-shoe pressure data processing

Data collected with the Pedar system was exported to Matlab for further analysis with a custom Matlab programme written by a fellow researcher at the University of Salford. This program was developed to analyse the PP data for a previous European Union project (SSHOES) and was modified slightly to analyse the data from this study. Despite being used at University, this Matlab program has not been published or shared with any other institution. The program first separated the data for each insole condition into separate blocks, corresponding to a continuous set of steps (approximately 17-22 steps per block) (Figure 6.4.). Each block was then subdivided into individual steps by setting a threshold value above which the foot was assumed to be in contact with the ground. This threshold was set manually for each set of data to just above the highest values of PP between steps, but never higher than 20 KPa. The first and last two steps were removed from each trial as these represented gait initiation and termination. Following trial and step division, the information was saved in a mat file format and subsequent processing was used to define appropriate pressure outcomes for each step.

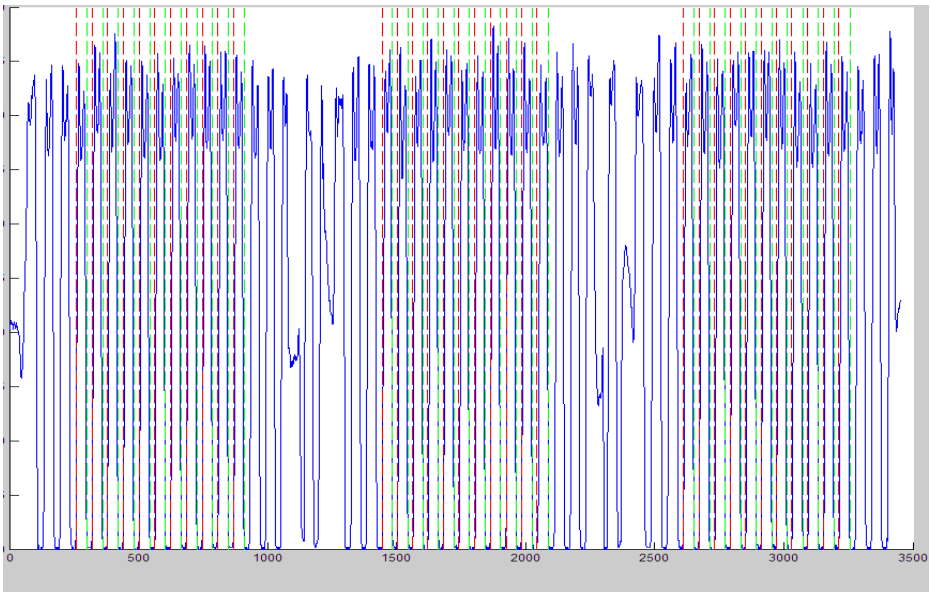

Figure 6.4: Step selection from walking graphs

Peak plantar pressure and the pressure time integral during the stance phase of walking was used to characterise the effect of varying the design features. This outcome was calculated for the 1st, 2-4th and 5th metatarsal heads as well as the hallux, regions reported to be the locations at most risk from ulceration (Weijers *et al.*, 2003). To define each mask region, specific sensor markers were selected (Figure 6.5) using the measurements of Cavanagh *et al*. (1994). The peak pressure (PP) and pressure-time integral (PTI) were calculated for each area. These outcomes were calculated for each step of each walk and then averaged across all steps to give a single value for each region.

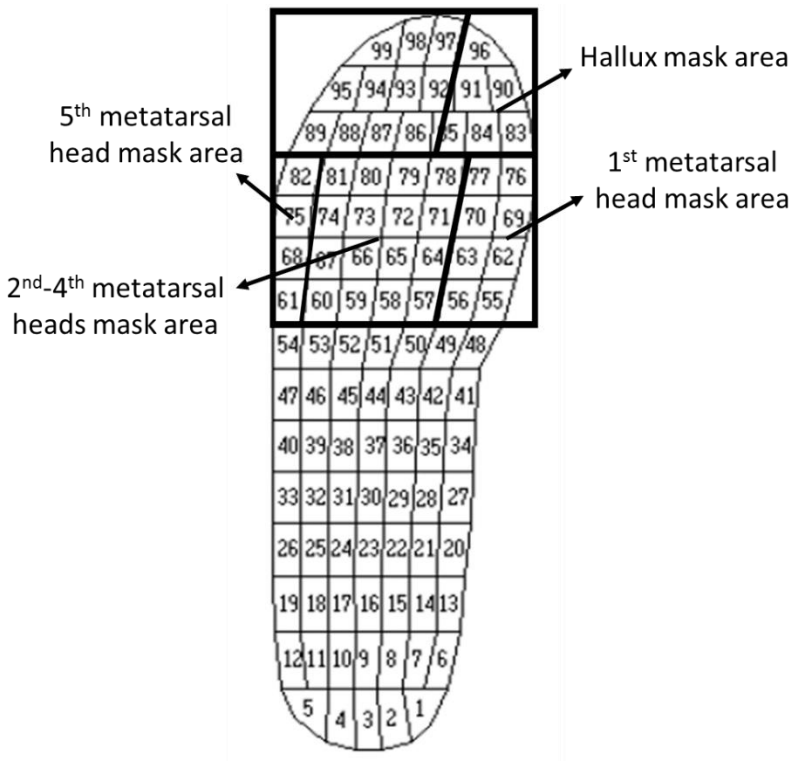

Figure 6.5: Pedar mask used in the study

These processed data were then exported to Excel so that the PP and PTI data were available for each visit, each region, each side and each condition. All these data were then combined on another excel sheet to allow the comparison between both visits per mask area, side and condition. SEM and ICC were then used to quantify the between-day variations in peak pressure and the pressure time integral across the different anatomical regions for each condition.

6.5.2 Statistical analysis

The SEM can be used to quantify how accurately repeated measurements can be obtained across a range of individuals. It quantifies this agreement as an average within-subject standard deviation, obtained by averaging the spread of measurements for each individual across the whole group. It can be quantified as the SD of the differences between repeated measurements (SDd) (Weir, 2005, Ramanathan *et al.*, 2010)

$$SEM = \frac{SDd}{\sqrt{2}}$$

ICC, on the other hand, quantifies the extent to which measurements can distinguish between patients despite measurement errors. The difference between this measurement and the SEM is that SEM only captures the actual variability in the measurement; it does not distinguish between patients. The ICC ranges from 0 to 1, with 0 indicating a large degree of inconsistency and 1 showing perfect reliability. It is important to understand that reliability captures the size of the measurement error relative to the variability across the group. This means that the higher the error, the lower the ICC. Accordingly, ICC can be calculated from SEM as follows:

$$ICC = 1 - \left(\frac{SEM}{SD}\right)^2$$

SEM and ICC were calculated for PP and PTI for all conditions, for each side and anatomical region. SEM results for PP and PTI are displayed in the next section within a table in the units of the pressure measurement, KPa. Also, average PP and PTI values are also presented in order to illustrate how reproducibility compares to typical pressure values. Low SEM values demonstrate good agreement between measurements, whereas, ICC values range from 0 to 1, with values close to 1 representing high repeatability. Finally, to have a representative value characterising the overall reproducibility for all contoured insoles, values of ICC and SEM were averaged across sides and all conditions.

6.6 Results

6.6.1 Sample and variables included

In this study (n = 8) there was a total of 5 males and 3 females, with a mean age of 59.5 ± 16.76 years, ranging from 25 to 78 years old. The participants were overweight to obese, with a mean body mass index (BMI) of 29.58 ± 4.4 kg/m^2 ranging from 23.05 to 34.11 kg/m^2.

In this study, the PP values for each one of the different insole conditions collected on the second and third visits were analysed and are presented in the next sections. The different functional tests and motion data collected on the first visit were only analysed in the last study presented in this thesis (Chapter 8).

6.6.2 First metatarsophalangeal joint (1st MPJ)

The reproducibility under the 1st MPJ showed relatively low SEM values. However, these SEM values were approximately 15-20% of the mean PP, but approximately 20% for PTI (Table 6.1). The SEM values did not appear to differ substantially between the different insole conditions, nor was there any clear difference in agreement between the standard shoe and the contoured insoles (Table 6.1).

	SEM					
	Left PP (KPa)	**Right PP (KPa)**	**Mean PP (KPa)**	**Left PTI (KPa*s)**	**Right PTI (KPa*s)**	**Mean PTI (KPa*s)**
D + EVA	54.32	61.20	303.7	8.76	8.03	40.34
B + EVA	47.2	59.73	307.12	7.74	9.02	38.12
P + EVA	58.54	61.65	302.8	10.04	6.57	41.16
D + Poron	61.98	45.54	292.47	9	7.56	38.8
B + Poron	53.22	53.09	291.7	7.44	7.75	36.72
P + Poron	55.53	41.27	294.64	9.02	7.74	41.97
D + Void	46.27	49.94	315.11	8.77	9.27	39.85
B + Void	44.73	69.4	313.19	8.15	8.82	39.67
P + Void	44.98	57.24	316.89	8.57	7.94	43.26
SShoe	57.87	54.44	301.41	11.47	7.97	39.22
Average	52.46	55.35	**303.9**	8.896	8.067	**39.91**
Total average	**53.91**			**8.4815**		

Table 6.1: Average SEM results for the 1st metatarsal head per side. PP: peak pressure; PTI: pressure-time integral; P: proximal metatarsal bar; B: base metatarsal bar; D: distal metatarsal bar; SShoe: standard shoe.

For the 1st MPJ, ICC values were low to moderate, ranging between 0.4 and 0.7. Similar to the SEM data, the ICC values did not appear to differ substantially across the different insole conditions. However, a difference between sides was found for both PP and PTI, with the resulting PTI differences greater than those for PP. In terms of the reliability, the mean ICC for PP (0.62) was slightly higher than that for the PTI (0.56). However, both would be considered moderate reliability (Table 6.2).

	ICC			
	Left PP (KPa)	**Right PP (KPa)**	**Left PTI (KPa*s)**	**Right PTI (KPa*s)**
D + EVA	0.57	0.67	0.41	0.68
B + EVA	0.67	0.64	0.37	0.59
P + EVA	0.55	0.7	0.46	0.76
D + Poron	0.5	0.73	0.45	0.7
B + Poron	0.63	0.6	0.45	0.67
P + Poron	0.51	0.75	0.5	0.69
D + Void	0.69	0.63	0.42	0.65
B + Void	0.75	0.55	0.49	0.56
P + Void	0.48	0.68	0.5	0.7
SShoe	0.56	0.59	0.44	0.71
Average	0.591	0.65	0.449	0.671
Total average	**0.62**		**0.56**	

Table 6.2: Average ICC results for 1st metatarsal head per side. PP: peak pressure; PTI: pressure-time integral; P: proximal metatarsal bar; B: base metatarsal bar; D: distal metatarsal bar; SShoe: standard shoe.

6.6.3 Central metatarsophalangeal joints

SEMs for PP and PTI under the metatarsal heads were relatively low. Although there were some side-to-side differences for PP, typical SEM values were around 15-20% of the mean PP for the left foot and 20% of the average for the right foot (Table 6.3). These differences between sides were not found in PTI, where SEM values were approximately 20% of the mean. For the PTI, there were no striking differences between SEM values across different conditions tested or for the control condition.

	SEM					
	Left PP (KPa)	**Right PP (KPa)**	**Mean PP (KPa)**	**Left PTI (KPa*s)**	**Right PTI (KPa*s)**	**Mean PTI (KPa*s)**
D + EVA	31.82	47.75	243.71	8.12	7.28	40.66
B + EVA	35.86	53.93	224.05	7.93	8.97	37.34
P + EVA	43.13	32.26	243.67	8.93	8.94	43.32
D + Poron	29.49	41.1	227.22	6.92	7.34	39.71
B + Poron	34.15	53.21	217.47	7.31	6	36.63
P + Poron	45.14	35.34	248.98	9.12	6.24	43.36
D + Void	38.39	48.6	248.7	9.42	7.2	38.33
B + Void	38.08	61.65	239.02	8.5	9.79	37.62
P + Void	52.03	39.52	270.81	7.46	8.44	43.49
SShoe	46.14	71.38	252.14	7.65	8.51	39.84
Average	39.423	48.474	**241.57**	8.136	7.871	**40.33**
Total average	**43.94**			**8.0035**		

Table 6.3: Average SEM results for central metatarsal heads per side. PP: peak pressure; PTI: pressure-time integral; P: proximal metatarsal bar; B: base metatarsal bar; D: distal metatarsal bar; SShoe: standard shoe.

Under the central metatarsal heads, the values for ICC were low to moderate, ranging between 0.4 and 0.7 (Table 6.4). In line with the findings for the SEM, the PTI appeared to be a slightly more reliable measure (higher ICCs) that PP. Again, there was minimal variability of ICC across the different insole conditions.

	ICC			
	Left PP (KPa)	**Right PP (KPa)**	**Left PTI (KPa*s)**	**Right PTI (KPa*s)**
D + EVA	0.53	0.46	0.48	0.63
B + EVA	0.49	0.39	0.46	0.42
P + EVA	0.41	0.63	0.39	0.48
D + Poron	0.56	0.54	0.64	0.62
B + Poron	0.53	0.34	0.51	0.63
P + Poron	0.39	0.58	0.49	0.65
D + Void	0.57	0.48	0.44	0.71
B + Void	0.56	0.38	0.47	0.42
P + Void	0.48	0.55	0.6	0.52
SShoe	0.44	0.42	0.53	0.54
Average	0.496	0.477	0.501	0.562
Total average	**0.4865**		**0.5315**	

Table 6.4: Average ICC results for central metatarsal heads per side. PP: peak pressure; PTI: pressure-time integral; P: proximal metatarsal bar; B: base metatarsal bar; D: distal metatarsal bar; SShoe: standard shoe.

6.6.4 Fifth metatarsophalangeal joint (5th MPJ)

The reproducibility of plantar pressures under the 5th metatarsal head showed relatively small SEM values (Table 6.5). Nevertheless, both PP and PTI values for the SEM were approximately 25-30% of the mean PP (Table 6.5). Similar to the other regions, there was minimal variability in the SEM across conditions for both PP and PTI and the standard shoe did not appear to be associated with better reproducibility.

	SEM					
	Left PP (KPa)	**Right PP (KPa)**	**Mean PP (KPa)**	**Left PTI (KPa*s)**	**Right PTI (KPa*s)**	**Mean PTI (KPa*s)**
D + EVA	34.74	32.98	124.53	12.24	9.3	31.62
B + EVA	29.12	30.45	122.49	8.84	8.94	29.27
P + EVA	35	32.35	121.16	12.32	9.64	29.42
D + Poron	24.04	30.39	115.46	11.53	7.22	27.39
B + Poron	25.75	31.31	115.77	7.8	7.23	26.56
P + Poron	31.71	30.3	123.02	11.32	7.7	30.93
D + Void	30.12	32.33	122.29	10.04	9.56	29.39
B + Void	35.49	28.71	126.1	12.05	10	32.05
P + Void	30.06	26.82	124.75	10.29	9.46	31.86
Sshoe	33.00	20.47	108.98	8.24	6.18	38.56
Average	30.90	29.61	**120.45**	10.467	8.523	**30.70**
Total average	**30.26**			**9.495**		

Table 6.5: Average SEM results for 5th metatarsal head per side. PP: peak pressure; PTI: pressure-time integral; P: proximal metatarsal bar; B: base metatarsal bar; D: distal metatarsal bar; SShoe: standard shoe.

ICC values under the central metatarsal heads were low to moderate, ranging from 0.4 to 0.8, slightly higher than other anatomical regions. However, in line with the findings from other areas, reliability was slightly higher for the PTI and there was also minimal variability between conditions.

	ICC			
	Left PP (KPa)	**Right PP (KPa)**	**Left PTI (KPa*s)**	**Right PTI (KPa*s)**
D + EVA	0.61	0.45	0.49	0.61
B + EVA	0.7	0.44	0.66	0.59
P + EVA	0.61	0.51	0.49	0.44
D + Poron	0.7	0.49	0.62	0.64
B + Poron	0.7	0.54	0.73	0.65
P + Poron	0.69	0.46	0.68	0.65
D + Void	0.68	0.45	0.66	0.66
B + Void	0.67	0.5	0.6	0.49
P + Void	0.71	0.5	0.7	0.51
SShoe	0.75	0.61	0.67	0.82
Average	0.682	0.495	0.63	0.606
Total average	**0.5885**		**0.618**	

Table 6.6: Average ICC results for 5th metatarsal head per side. PP: peak pressure; PTI: pressure-time integral; P: proximal metatarsal bar; B: base metatarsal bar; D: distal metatarsal bar; SShoe: standard shoe.

6.6.5 Hallux

The hallux showed the highest SEM results across all the masks studied illustrating low levels of reproducibility. SEM values for both PP and PTI were approximately 35-40% of the mean PP. However, variability across conditions was also low for both PP and PTI.

	SEM					
	Left PP (KPa)	**Right PP (KPa)**	**Mean PP (KPa)**	**Left PTI (KPa*s)**	**Right PTI (KPa*s)**	**Mean PTI (KPa*s)**
D + EVA	77.01	102.34	245.84	16.53	16.06	42.24
B + EVA	73.49	93.49	240.31	17.14	14.35	41.7
P + EVA	76.88	100.54	260.89	18.65	15.74	42.43
D + Poron	79.31	89.76	225.12	17.54	15.52	41.05
B + Poron	70.66	85.84	240.11	17.9	14.68	40.43
P + Poron	73.43	89.53	247.72	16.56	14.58	42.53
D + Void	70.91	96.73	248.64	16.83	13.8	41.79
B + Void	74.18	102.13	244.92	19.08	15.73	42.4
P +Void	69.22	96.66	250.6	16.6	16.61	36.32
SShoe	90.8	88.61	212.09	15.93	12.32	43.93
Average	75.59	94.56	**231.62**	17.276	14.939	**41.45**
Total average	**85.08**			**16.1075**		

Table 6.7: Average SEM results for hallux per side. PP: peak pressure; PTI: pressure-time integral; P: proximal metatarsal bar; B: base metatarsal bar; D: distal metatarsal bar; SShoe: standard shoe.

ICC values under hallux were the lowest obtained across all anatomical regions, ranging from 0.4 to 0.6. However, slightly higher ICCs (better reliability) were observed for PTI in comparison to PP. The variability of the ICC results across the different conditions was low and, again there was no clear difference between the standard and contoured insole conditions.

	ICC			
	Left PP (KPa)	**Right PP (KPa)**	**Left PTI (KPa*s)**	**Right PTI (KPa*s)**
D + EVA	0.46	0.5	0.38	0.56
B + EVA	0.47	0.53	0.41	0.59
P + EVA	0.45	0.51	0.39	0.53
D + Poron	0.45	0.52	0.44	0.57
B + Poron	0.52	0.52	0.39	0.61
P + Poron	0.44	0.46	0.42	0.62
D + Void	0.52	0.5	0.44	0.66
B + Void	0.51	0.5	0.4	0.54
P + Void	0.45	0.51	0.51	0.55
Sshoe	0.43	0.52	0.43	0.66
Average	0.47	0.507	0.421	0.589
Total average	**0.48**		**0.505**	

Table 6.8: Average ICC results for hallux per side. PP: peak pressure; PTI: pressure-time integral; P: proximal metatarsal bar; B: base metatarsal bar; D: distal metatarsal bar; SShoe: standard shoe.

6.7 Discussion

6.7.1 Overview of the main findings

The main aim of this study was to investigate the agreement and the repeatability of plantar pressure measurement in people with diabetes and neuropathy. Agreement calculations establish how accurately the same measurement on separate occasions can be taken across subjects. SEM is an agreement statistic that is expressed in the same units as the outcome. Therefore, the results were presented along with the average PP and PTI to interpret variability in the context of typical pressure values. The SEM data demonstrated a moderate level of experimental error, especially in the PP values. Importantly, these values were relatively large when compared with the average mean pressures. Specifically, SEMs under the 1st metatarsal head, central metatarsal heads and under the 5th metatarsal head were around 25-30% of the average PP in the corresponding region. Notably, the overall magnitude of the SEM values for PTI was similar. For both metrics (PTI and PP), reliability was found to be poor in the hallux region, with SEM values of 35-40% of the mean and PP of 30-35% of the mean for PTI.

SEM values for PTI were very similar to those observed for PP measurements in all of the regions. The high correlation between PP and PTI has been established previously (Keijsers *et al.*, 2010, Waaijman&Bus, 2012) and the added value of reporting both outcomes has been questioned (Bus&Waaijman, 2013). Most papers published discuss the results for PP rather than PTI and the added value of PTI is minimal when both are reported (Bus&Waaijman, 2013). The region where the PTI may add some value is the heel, probably because the variability in the shape of the peak pressure-time curve is higher in the heel than in other regions given the foot progression during gait (Bus&Waaijman, 2013). In studies where differences between PTI and PP were found, these were not explained or not meaningful for the study (Bus&de Lange, 2005, Bacarin *et al.*, 2009, Bus *et al.*, 2009, Rao *et al.*, 2010). Furthermore, there are different approaches to calculating PTI, which has to be taken into consideration when comparing results with published literature. Overall, our results show that reproducibility of both outcomes is similar, further supporting the consensus that there is no added value in reporting PTI in addition to PP.

ICC was calculated to quantify reliability and expressed from 0 to 1, with an ICC of above 0.8 demonstrating excellent reliability. Our results for ICC were quite similar across the different anatomical regions tested for both PP and PTI, ranging from 0.4 to 0.6. However, for all of the regions, no distinct differences were observed between the PP and the PTI ICCs. Overall, the ICC results across all anatomical regions showed relatively low values indicating only moderate to poor reliability. This illustrates that it may be difficult to differentiate between subjects given the level of error in the measurement. However, there did appear to be sufficient consistency in the measurement to potentially identify differences between different insoles designs. These ideas are discussed in more detail below.

An interesting finding of this study was that the SEM was considerably higher for the hallux region when compared to the metatarsal head areas. One possible explanation for this difference might be related to the biomechanical function of the hallux, which acts to maintain balance during walking (Hughes *et al.*, 1990, Miyazaki&Yamamoto, 1993, Hall&Nester, 2004). Most of the insoles investigated in this study incorporated a metatarsal bar, which will result in flexion of the metatarsophalangeal joints and therefore alter the normal position of the hallux. This altered position could lead to a more variable walking pattern and consequently, higher SEMs and lower ICCs.

Reproducibility results were not very high but were stable across all conditions and most of the mask regions, implying that the low reliability resulted from the participants rather than the device or the different insoles tested. This idea is consistent with the observation that SEM values were similar between the contoured and flat insoles. The participants in this study were relatively elderly people with diabetes and neuropathy (59.5 ± 16.76 years) (see section 6.6.1.). This group may have inconsistent gait patterns because of their age and neuropathy (Allet *et al.*, 2008). Indeed, there is evidence of an altered and less efficient gait in patients with diabetes and neuropathy (Ko *et al.*, 2011, Martinelli *et al.*, 2013). Lalli *et al.* (2013) compared gait variability for step length and velocity of healthy subjects and subjects with DM and neuropathy, concluding that the cohort with diabetes and neuropathy had a more variable gait that the healthy group. These findings support the idea that the variability in this study is due to the subject rather than the device or protocols used for plantar pressure collection. Interestingly, all previous studies investigating the reproducibility of plantar pressure collection recruited healthy

subjects rather than high-risk patients such as subjects with DM and neuropathy. Therefore, their results may not extrapolate to medium or high-risk populations for whom plantar pressure measurements are of key importance. Accordingly, plantar pressure measurements should be interpreted carefully when testing patients with diabetes and neuropathy.

The most surprising aspect of the results from this study was the considerably lower reproducibility in plantar pressure observed in this study in comparison to the reproducibility reported in the literature(Murphy *et al.*, 2005, de Castro *et al.*, 2014, Godi *et al.*, 2014). However, this difference may be explained by the characteristics of the sample rather than the measurement device or the data collection protocol followed. As explained above and which will be explored in more detail in the following sections, the study participants were old with neuropathy. Both conditions have a significant effect on the gait and balance of the subject, which could have an impact on the reproducibility.

6.7.2 Comparison of findings with previous repeatability research

Several other studies have assessed the repeatability of plantar pressure collection with Pedar and other in-shoe measurement systems. These investigations have used a range of different statistical tests in order to establish reliability (Hurkmans *et al.*, 2006, Putti *et al.*, 2007, Ramanathan *et al.*, 2010), with some using the ICC (Murphy *et al.*, 2005, Gurney *et al.*, 2008, de Castro *et al.*, 2014, Godi *et al.*, 2014), but none using the SEM. SEM was selected for this study as it provides a clear indication of the difference between repeated measurements across subjects. Furthermore, the SEM is in the units of the measurement, helping interpretation and comparison with the data collected. This test, in combination with the ICC, provides a better understanding not only of the measurement error but the differences between subjects.

Ramanathan *et al.* (2010) studied the repeatability of Novel Pedar insoles using the coefficient of variation. They recruited 27 healthy male subjects and tested the insole in off-the-shelf running shoes on two occasions separated by one week. The coefficient of variation uses the SEM, dividing it by the mean of all measurements and multiplying it by 100 to express the typical error as a percentage of the mean. This statistical approach is correct, but an individual SEM would have been to test agreement on the measurements. They concluded that PP and PTI are repeatable under the metatarsals

heads and hallux with a coefficient of variation of 9.1 – 17.4 for PP and 18.4 – 31.9 for PTI. Although they showed overall higher agreement, the pattern across the different regions was consistent with the findings from this study, with greater repeatability under metatarsal heads in comparison to the hallux. However, it is interesting that they found PTI to be less repeatable than PP, which may be due to study participants; they used healthy young subjects, our study focused on patients with diabetes and neuropathy.

The coefficient of repeatability has also been used to quantify repeatability of Novel Pedar insoles. Putti *et al*. (2007) used standard running shoes with 53 participants and two test sessions 12 days apart. They performed a repeated measures ANOVA test to investigate possible differences between days, followed by calculation of the SD of the between walk differences to determine the coefficient of repeatability, expressed as a percentage of the mean. This approach is problematic as ANOVA analysis is designed to test for statistical differences between repeat testing rather than to quantify the absolute error in repeated measurements. Putti *et al.* (2007) also used the coefficient of repeatability, which is the value below which the absolute differences between two measurements would lie, with 0.95 probability. It is calculated by multiplying the SEM by 2.77 (2 times 1.96). They expressed the coefficient of repeatability as a percentage of the mean PP. With this approach, they found high levels of repeatability with the hallux being the least repeatable, with a 7.7% of the mean PP. Again, they observed similar trends to our data, with better reproducibility under metatarsal heads than the hallux. Interestingly, like Ramanathan *et al.* (2010), they found better repeatability for PP than PTI, which was not observed in our study.

Three different studies have used the ICC to quantify repeatability of repeated plantar pressure measurements. Murphy *et al*. (2005) recruited sixteen healthy subjects, collecting data on two separate days with the subjects wearing their own shoes. In their analysis, they did not use the peak pressures or pressure time integrals but instead calculated normalised pressures for each masking area across the whole foot. They divided the combined pressure in each region by the total pressure beneath the entire foot at midstance. To calculate the masking areas, they used percentages of foot length and width, which may not be the most appropriate approach. One problem with this calculation is that sensors located on the metatarsal heads may have been included within the toes region. Despite this limitation, Murphy *et al.* (2005) obtained similar levels of

reproducibility to our study with ICCs in the forefoot areas of 0.6 and 0.7 compared to 0.5-0.6 in the current study.

Godi *et al*. (2014) also quantified the repeatability of in-shoe pressure collection using the ICC. To this end, they recruited 16 young healthy subjects and collected data on two walking sessions two days apart. All subjects used the same standard running shoes with the Pedar insoles located inside the shoe, between the foot and the inside of the shoe. They calculated PP across the whole foot and did not use mask areas to investigate pressures at different anatomical structures. This approach, of not using a mask, may not be appropriate if the aim is to understand the repeatability of plantar pressure collection as peak pressures are very different across the whole foot and averaging them might lead to misleading conclusions. With their approach, they obtained an ICC for peak pressure of 0.95 which is considerably higher than our data and that of Murphy *et al.* (2005). As mentioned previously, this difference could be explained by the study population used, healthy young subjects versus patients with diabetes and neuropathy.

The repeatability of in-shoe plantar pressure data was also characterised by de Castro *et al.* (2014) using the ICC test. However, in their study, they assessed the reliability of both the WalkingSense system and the Pedar system at the same time. They recruited 40 young healthy participants, placing both insole systems, one on top of each other, inside standard ballet running shoes. This approach may not be appropriate as systems can interfere and influence each other's measurement when in direct contact. Moreover, they compared the first right and left steps of two different walks. It has been suggested that the first steps of a data collection set should be removed and that a minimum of 20 steps is required to obtain enough data to be comparable (Melvin *et al.*, 2014). Despite these limitations, they demonstrated higher ICC values (> 0.8 in most of the areas studied) than in the current study. They also found similar levels of repeatability between the PP and PTI, which is in agreement with our results.

Several papers have studied the reliability of in-shoe plantar pressure collection with different approaches. However, there is no previous research regarding the reproducibility of plantar pressure measurements in patients with diabetes and neuropathy, which is the population most affected by complications resulting from

elevated peak pressures. Moreover, there are no previous studies exploring the reproducibility of plantar pressure collection on customised contoured insoles, which are commonly prescribed to offload pressures in medium or high-risk patients. Interesting, all previous research published found higher levels of agreement and reliability than those observed in the current study. It is possible that this is due to the variability in the gait of people with diabetes and neuropathy (Allet *et al.*, 2008) and must be taken into consideration when interpreting the results of studies analysing plantar pressures in this cohort.

6.7.3 Limitations of this study

The main limitation of this study is the small sample size (n = 8), potential participants were reluctant to attend this type of testing on two separate days (which would have meant them attending on three different days in total). Nevertheless, it was felt that 8 subjects would be sufficient to characterise the level of variability between repeated sessions. Furthermore, this number was only slight below the sample size of 10 used in some other repeatability studies (Gurney *et al.*, 2008, Sawacha, 2013). Another limitation of this study was the relatively long period between repeated tests, typically 2-4 weeks. Although previous repeatability studies typically report repeatability between sessions separated by approximately one week (Ramanathan *et al.*, 2010), a longer period was chosen in this study to inform the interpretation of data from subsequent studies in this thesis. Specifically, to establish a clear threshold above which a change in pressure was the result of a change in insole design, rather than due to variability in the measurement. However, it is possible that the lower level of reproducibility observed in this study may have been, in part, the result of the longer time period.

Self-selected walking speed for each subject was used in this study by calculating an average from five separate preliminary walking trials. All subsequent trials were then accepted if the walking speed was within a ±10% tolerance. Although for many participants, it was possible to work to ±5% tolerance, the participants with diabetes were often not able to repeatedly walk within this tightly controlled speed. Therefore, speed tolerance was increased to ±10% to ensure participants could complete the testing before becoming fatigued. However, research has shown that walking speed can influence plantar pressures (Segal *et al.*, 2004), so, it is possible that some of the variability in the

measurements could be attributed to differences in walking speed between the two days. Nonetheless, a tolerance of 10% was adopted to ensure data could be collected from every participant.

6.7.4 Conclusions and implications for subsequent plantar pressure analysis

Peak pressure (PP) is the most common outcome used to quantify plantar foot loading in diabetic foot research. This is because diabetic foot ulceration has been associated with the presence of elevated PP (Frykberg *et al.*, 1998, Kastenbauer *et al.*, 2001). Pressure time integral (PTI) is often reported and has also been associated with foot ulceration, but this association has only been demonstrated through retrospective analysis (Stess *et al.*, 1997). Interestingly, Waaijman *et al*. (2012) used the Pearson correlation coefficient to study the correlation between PP and PTI, concluding that they are highly interdependent. These findings suggest that these parameters may be interchangeable and the value of reporting both parameters in the same study may be limited (Keijsers *et al.*, 2010, Waaijman&Bus, 2012). The results of our study suggest that the reproducibility of PTI and PP is very similar and therefore support the practice of only reporting PP, rather than both and PP, given that only PP has been definitively associated with ulceration.

This is the first study investigating the reproducibility of plantar pressure measurements in medium-risk patients while wearing customised insoles. All previous research in this area has been performed on healthy subjects, despite elevated peak pressures being a risk factor for foot ulceration. Although the effectiveness of insoles for reducing pressure has been studied extensively, the interpretation of these data has been based on repeatability studies from healthy subjects. However, the results of this study show that measurements from people with diabetes and neuropathy have a high level of variability. These results need to be taken into consideration when interpreting the results of future studies testing the efficacy of different insole designs.

The data from this study was used as a basis for interpreting change in plantar pressure measures associated with different insole designs in the final experimental chapter which focused on predicting individual pressure responses. Specifically, the aim

was to set a threshold for PP above which we could be confident that changes were real and not the result of variability in the measurement. To this end, the highest values for the SEM results for PP under each anatomical region was selected and set as a threshold to filter noise on the measurement and false results (Table 6.9.). Accordingly, given the similarity of the SEM values for PP across the metatarsal heads, the same threshold was set for all these regions. However, large differences were found between the SEM results on PP values for the hallux and the rest of the anatomical regions, so it was decided to set a different threshold for this region (Table 6.9.), a 55 KPa threshold was set for PP under metatarsal heads and 85 KPa for the hallux.

	1st metatarsal head	Central metatarsal heads	5th metatarsal head	Hallux
SEM result	53.91 KPa	43.94 KPa	30.26 KPa	85.08 KPa
Threshold set	55 KPa	55 KPa	55 KPa	85 KPa

Table 6.9: PP SEM results and thresholds set per anatomical region.

These thresholds were especially relevant for the second quantitative study (Chapter 8), in which the aim was to explore individual pressure responses and to understand if they were associated with individual biomechanical/clinical variables. Accordingly, when a participant showed a reduction of pressure equal or higher than the threshold selected (55 KPa for metatarsal heads and 85 KPa for the hallux), was considered as a positive response. On the other hand, if the pressure reduction was lower than the threshold, or a PP increase was found, they were considered as a non-responder. However, the thresholds were less important for the study described in the next chapter which was aimed at understanding the mean pressure responses to different insole designs. For this type of analysis, individual variability will typically average out provided the cohort is sufficiently large.

7 Understanding the effect of systematically varying insole design characteristics on in-shoe plantar pressure

7.1 Background

Insoles have shown to be effective for offloading peak pressures (PP) in patients with diabetes and neuropathy. There are numerous possible design approaches which can be used to achieve offloading, but custom-made insoles have been shown to be the most effective (Guldemond *et al.*, 2007, Zequera *et al.*, 2007, Healy *et al.*, 2012). However, a total contact insole on its own may not be sufficient to reduce PP in the diabetic foot (Hastings *et al.*, 2007) and so, it is often necessary to incorporate additional changes to the contours of the insole. The most common addition used to reduce PP under the forefoot is a metatarsal bar, which has been shown to be effective under the metatarsal heads (Hsi *et al.*, 2005). Some authors combined custom-made orthoses and metatarsal bars resulting in the most efficient offloading design (Hodge *et al.*, 1999, Bus *et al.*, 2004, Mueller *et al.*, 2006, Guldemond *et al.*, 2007, Cheung&Zhang, 2008). However, only one study by Owings (2008) customised the metatarsal bar based on participant's PP and in a fully customised insole. Their results showed that full insole customization is the best approach to reducing PP under the forefoot of the diabetic foot.

Soft and cushioning materials are also commonly used by practitioners in insole design to offload PP. However, a broad range of materials with different physical properties is available for manufacturing insoles. These physical properties, such as shock absorption and hardness, should be considered thoroughly to achieve the maximal therapeutic effect (Kang *et al.*, 2006). Materials normally used in podiatry can be classified into three main types depending on their function in the insole, adaptation or accommodation, cushioning and filling materials (Fauli *et al.*, 2008). The material on the top, which is in contact with the foot, is the adaptation or accommodation material and helps to homogenise plantar pressures. Under this layer is the cushioning material, normally located under the areas of PP in order to absorb and reduce them. Finally, the filling material conforms to the rest of the insole and provides motion control and stability

to the insole. The physical properties of the most commonly used materials in podiatric clinical practice have been studied and shown to be an effective in reducing PP (Paton *et al.*, 2007, Fauli *et al.*, 2008). Some authors have tested the effect of insoles manufactured with cushioning materials in PP concluding that they are an appropriate approach to reduce PP (Burns *et al.*, 2008, Healy *et al.*, 2012). However, these studies used the cushioning materials to manufacture the whole insole, rather than using them only under the regions of peak pressure. To date, only Actis *et al.* (2008) have tested the effect of using used cylinders of cushioning material under the metatarsal heads and found them to be a suitable approach for reducing PP.

Different approaches have been used to reduce PP using a range of different insole designs and materials. The combination of a cushioning material with a metatarsal bar is an effective approach for plantar pressure reduction. However, there are no studies investigating the effect of material combined with customised insoles and a metatarsal bar in PP. Therefore, further research is needed to identify the optimum insole design combination which could be used to achieve maximal PP reduction. To this end, fully customised insoles were designed for each participant based on both foot shape and plantar pressures, combining the additions previously shown to be most effective in the literature, metatarsal bar and cushioning material. To design these insoles, a 3D foot scan was used to customise the insole top surface and plantar pressure data to tailor the metatarsal bar shape and the area for cushioning material under the metatarsal heads (see Chapter 5). As a result, a customised contoured insole was obtained with a customised metatarsal bar and cushioning forefoot material. To understand the optimum metatarsal bar position, it was moved 2% of the length of the foot distally and proximally. The two cushioning materials used under the forefoot were the most commonly prescribed by podiatrists, soft EVA and Poron. This approach was used to address the following research questions:

1. What is the effect of systematically varying the metatarsal bar position in combination with cushioning material on in-shoe plantar pressures?
2. Which is the mean optimum design?
3. What is the effect of each insole configuration when compared to the control condition?

4. How much additional value is there is in individually choosing specific design features?

7.2 Study design

A total of 60 subjects with diabetes and neuropathy were recruited and asked to visit the Gait Laboratory at Salford University on two different occasions. On the first visit, barefoot plantar pressures with the Novel Emed pressure platform and a 3D scan of each foot were collected. These data were used to fully customise the insole designs to both foot shape (top surface of the insole) and plantar pressures (metatarsal bar distal line shape, see Chapter 5). A total of 9 customised insoles were designed for each participant by systematically varying the position of the metatarsal bar and the cushioning material under the metatarsal heads (see Chapter 5). Subjects were asked to return for a second testing once their insoles had been manufactured. They were then instructed to walk, wearing each one of the insoles, while pressure data was collected using the Novel Pedar system. For a detailed description of the data collection process, see Chapter 5.

7.3 Data analysis

7.3.1 In-shoe pressure data analysis:

A custom Matlab programme was written to process the pressure data. Each insole condition data file consisted of a minimum of 4 trials (minimum depending on additional trials) which were separated out into 4 “blocks” of steps (17-22 steps per block approximately) representing the trials (Figure 7.1). Each trial was then subdivided into steps using a manually set threshold and the first and last two steps were removed from each trial as these represented gait initiation and termination. Following trial and step division, the information was saved in a mat file format. Once the steps were defined, mean peak pressure could be calculated.

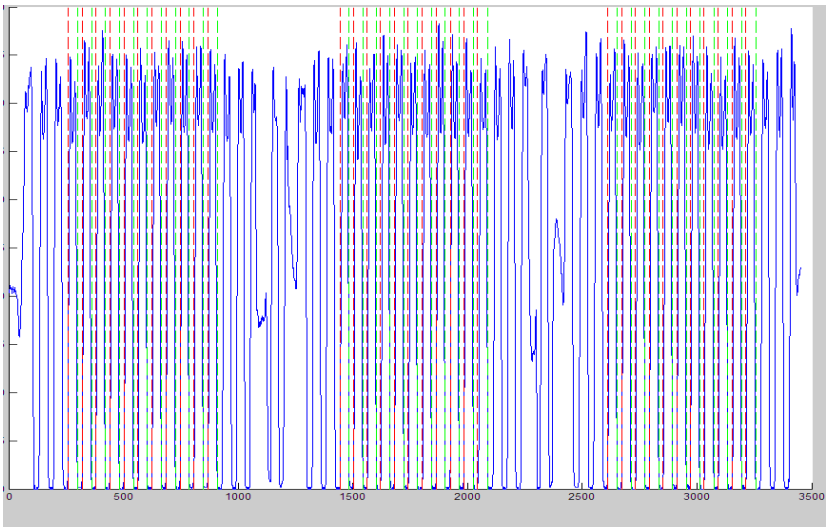

Figure 7.1: Step selection on

PP pressure during the stance phase of walking was used to characterise the effect of varying the design features. PP has been shown to be a key risk factor for ulceration in patients with peripheral neuropathy (Abouaesha *et al.*, 2001, Patry *et al.*, 2013) and was, therefore, the most appropriate outcome for this study. PP and pressure-time integral (PTI) have been shown to be highly correlated (Keijsers *et al.*, 2010, Waaijman&Bus, 2012). However, there is only weak evidence to support the link between elevated PTI and increased ulceration, with only one paper using retrospective methods finding a correlation between PTI and ulceration risk (Stess *et al.*, 1997). Given the high correlation between PTI and PP as well as their similar reproducibility, only PP was used as an outcome in all of the analyses.

The PP was calculated for the 1st metatarsophalangeal joint, 2-4th metatarsal head, the hallux, and 5th metatarsal head. The first three plantar regions were reported to be the locations at most risk from ulceration (Weijers *et al.*, 2003). The regions were defined using the measurements of Cavanagh&Ulbrecht (1994) and the pressure measurements from the respective sensors were used to calculate the peak pressures for each separate step. It was then averaged across all steps to give a single PP value for each region (Figure 7.2). Using this approach, PP was obtained for each of the five regions, for each condition for each participant.

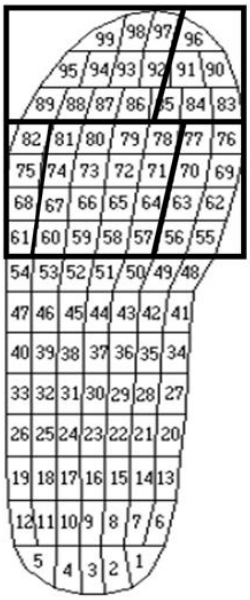

Figure 7.2: Different areas defined on the Pedar mask used in the study

7.4 Statistical analysis

Different statistical methods were used in order to answer each of the four research questions:

1. **The effect of systematically varying metatarsal bar position in combination with cushioning material on in-shoe plantar pressures**

A two-way repeated measures ANOVA was conducted to understand the effect of material properties, metatarsal bar position and the combination of both in PP for each anatomical region. Bonferroni post hoc testing was then used to further understand the differences found by the ANOVA. Bonferroni corrects the p-value, dividing it by the number of variable pairs to produce a new p-value for each specific pairwise comparison test. Despite being a conservative test, a Bonferroni post hoc test was used. This was deemed appropriate due to the relatively large sample size (n=60) used in this study which will lead to low p-values for relatively small effect sizes. However, rather than perform pairwise comparisons between each different pair of insoles, pairwise comparisons were made between the three material properties (averaged across metatarsal bar position) and between the three metatarsal bar positions averaged (across material property).

2. **Identification of the mean optimum design**

The inter-subject variability in response to the different insole conditions was examined to identify the mean optimum insole design. Specifically, the insole condition that led to a minimal PP was selected for each one of the participants. This data was then used to obtain the distribution of optimal insole conditions across subjects and therefore, to identify the mean optimum design across participants. The choice of mean optimal design was then validated against the ANOVA analysis.

3. **Comparison of the different insole designs with the control condition**

A repeated measures ANOVA was performed to understand the differences in PP between the 9 different insole conditions and the control shoe for each anatomical region. The Bonferroni post hoc test was again used to identify pairwise differences between conditions. With this approach, there was a large number of pairwise comparisons which, with the Bonferroni correction will mean that the critical p-value was adjusted down by a considerable margin. However, the differences between the control and most of the insole conditions were relatively large. This combined with the large number of subjects (n=60) made it possible to use a Bonferroni correction to identified differences with a high level of confidence.

4. **Comparison of the individual optimal design with group optimal design and control shoe (How much additional value is there is in individually choosing specific design features?)**

To understand the potential effect of full individual customisation, an individual optimal design was identified for each participant in each anatomical region. This was achieved by identifying the insole design which was associated with the lowest PP value across all conditions. Then, this PP value was averaged across all participants to obtain the mean individual optimal design PP value. This value was then compared to the group mean PP value for the best group design (identified in research question 2) and also to the mean PP for the control shoe.

Results were calculated for all the different anatomical regions on both the left and right sides. The results obtained for both limbs were very similar and the number of

cases was 50% per limb. Given the large amount of data obtained, reporting the results for both limbs would have been redundant and not provided any relevant information. Accordingly, it was decided to only report the results obtained for the right side because for the majority of the general population, it is the dominant limb and the results from the left side were almost identical.

7.5 Results

7.5.1 Sample demographics

This study comprised a total of 40 males and 20 females, with a mean age of 65.93 ± 12.62 years, ranging from 25 to 87 years old. The subjects were overweight to obese, with a mean BMI of 29.41 ± 5.19 kg/m^2 ranging from 21.45 to 45.18 kg/m^2.

7.5.2 The effect of systematically varying metatarsal bar position in combination with cushioning material on in-shoe plantar pressures

In order to understand the effect of each one of the additions investigated in this study, a two-way repeated measures ANOVA was used with the Bonferroni post-hoc test.

7.5.2.1 1st metatarsal head

There was no significant change in PP as metatarsal bar position was moved distally ($p = 0.655$). However, when the material properties were varied, there was a significant change in PP ($p < 0.001$). The ANOVA analysis showed no interaction between material properties and metatarsal bar position ($p = 0.818$), indicating that the effect of the metatarsal bar position was consistent across the different materials.

		Mean Difference	Std. Error	95% CI		p
				Lower Bound	Upper Bound	
Material	Eva	222.689	9.627	203.426	241.952	<0.001
	Poron	219.865	9.402	201.052	238.678	
	Void	238.955	9.619	219.707	258.203	
Metatarsal bar position	Proximal	228.365	9.578	209.199	247.530	0.655
	Base	224.871	10.383	204.095	245.646	
	Distal	228.273	9.270	209.725	246.822	
Interaction		-	-	-	-	0.818

Table 7.1: Two-way repeated measures ANOVA results for material, metatarsal bar position and interaction of both.

The Bonferroni post hoc test revealed that both material conditions (Poron and EVA) lead to significantly lower PP in comparison to the Void condition ($p < 0.001$) (Table 7.2). However, no differences were observed between EVA and Poron.

Material		Mean Difference	Std. Error	95% CI		p
				Lower Bound	Upper Bound	
EVA	Poron	2.824	1.997	-2.097	7.745	0.488
EVA	Void	-16.266	2.820	-23.215	-9.316	<0.001
Poron	Void	-19.090	2.899	-26.234	-11.946	<0.001

Table 7.2: Pairwise comparisons with Bonferroni correction for the different materials tested under the 1st metatarsal head.

7.5.2.2 Central metatarsal heads

Significant differences in PP were found when the metatarsal bar position was moved distally ($p = 0.003$; Table 7.3). When material properties were varied, there was a significant change in PP ($p < 0.001$; Table 7.3). The ANOVA analysis showed that the interaction between the different metatarsal bar positions and the different material conditions had no significant effect on PP ($p = 0.754$; Table 7.3).

		Mean Difference	Std. Error	95% CI		p
				Lower Bound	Upper Bound	
Material	Eva	215.269	8.271	198.718	231.820	<0.001
	Poron	215.163	8.250	198.656	231.670	
	Void	234.292	8.856	216.571	252.012	
Metatarsal bar position	Proximal	217.805	8.338	201.121	234.489	0.003
	Base	216.408	9.502	197.394	235.422	
	Distal	230.510	8.335	213.832	247.188	
Interaction		-	-	-	-	0.754

Table 7.3: Two-way repeated measures ANOVA results for material, metatarsal bar position and interaction of both.

The Bonferroni post hoc test showed that both base (0) and distal (+2) metatarsal bar positions led to a significantly lower PP than the proximal position (-2) (Table 7.4). However, no differences were found between the base and distal metatarsal bar positions. Regarding material conditions, the test results showed that both cushioning materials Poron and EVA) led to significantly lower PP in comparison to the Void condition (Table 7.4). However, no differences were observed between EVA and Poron.

Metatarsal bar position		Mean Difference	Std. Error	95% CI		p
				Lower Bound	Upper Bound	
Proximal	Base	1.397	3.857	-8.107	10.901	1
Proximal	Distal	-12.705	4.192	-23.034	-2.375	0.011
Base	Distal	-14.102	5.316	-27.202	-1.001	0.031

Table 7.4: Pairwise comparisons with Bonferroni correction for the different metatarsal bar positions tested under central metatarsal heads.

7.5.2.3 5th Metatarsal head

The metatarsal bar position did not have a significant effect on PP ($p = 0.426$; Table 7.5). However, when material properties were varied, there was a significant change in PP ($p < 0.001$; Table 7.5). The ANOVA analysis showed that the interaction

between the metatarsal bar position and material had no significant effect on PP (p = 0.220)

		Mean Difference	Std. Error	95% CI		p
				Lower Bound	Upper Bound	
Material	Eva	109.444	5.086	99.267	119.622	<0.001
	Poron	109.507	5.089	99.324	119.689	
	Void	115.531	5.006	105.514	125.549	
Metatarsal bar position	Proximal	111.156	5.164	100.823	121.489	0.426
	Base	112.914	5.017	102.875	122.953	
	Distal	110.412	5.133	100.141	120.683	
Interaction		-	-	-	-	0.220

Table 7.5: Two-way repeated measures ANOVA results for material, metatarsal bar position and interaction of both.

The Bonferroni post hoc test revealed that both material conditions (Poron and EVA) led to a significantly lower PP when compared to the Void condition (Table 7.6). However, no differences were observed between EVA and Poron.

Material		Mean Difference	Std. Error	95% CI		p
				Lower Bound	Upper Bound	
EVA	Poron	-0.062	1.320	-3.315	3.190	1
EVA	Void	-6.087	1.552	-9.912	-2.262	0.001
Poron	Void	-6.025	1.815	-10.497	-1.552	0.005

Table 7.6: Pairwise comparisons with Bonferroni correction for the different materials tested under the 5th metatarsal head.

7.5.2.4 Hallux

Significant differences in PP were found (p = 0.043; Table 7.7) as the metatarsal bar position was moved distally. However, when the material properties were varied, there was no significant change in PP (p = 0.970; Table 7.7). The ANOVA analysis showed no interaction between material properties and metatarsal bar position (p = 0.696), indicating that the effect of metatarsal bar position was consistent across the different materials (Table 7.7).

		Mean Difference	Std. Error	95% CI		p
				Lower Bound	Upper Bound	
Material	Eva	233.589	13.323	206.929	260.250	0.970
	Poron	233.825	13.178	207.456	260.194	
	Void	233.255	13.109	207.024	259.485	
Metatarsal bar position	Proximal	233.455	13.399	206.645	260.266	0.043
	Base	229.328	13.099	203.118	255.539	
	Distal	237.886	13.336	211.200	264.571	
Interaction		-	-	-	-	0.696

Table 7.7: Two-way repeated measures ANOVA results for material, metatarsal bar position and interaction of both.

The Bonferroni post hoc test showed that the base metatarsal bar position led to a significantly lower PP than the proximal metatarsal bar position (p = 0.042; Table 7.8).

Metatarsal bar position		Mean Difference	Std. Error	95% CI		p
				Lower Bound	Upper Bound	
Proximal	Base	4.127	2.944	-3.129	11.382	0.499
Proximal	Distal	-4.430	3.730	-13.622	4.761	0.719
Base	Distal	-8.557	3.375	-16.874	-0.240	0.042

Table 7.8: Pairwise comparisons with Bonferroni correction for the different materials tested under the hallux.

7.5.3 Identification of the mean optimum design

To identify the mean optimum design, descriptive statistics were used to establish which combination of additions achieved the lowest PP. The control shoe was not included in the comparisons as it never resulted in a lower PP under the metatarsal heads. Moreover, the focus of this study was to better understand the effect of each of the additions rather than comparing them to the control shoe.

7.5.3.1 1st metatarsal head

The combination of Poron with each of the three metatarsal bar positions was the design which most frequently led to the lowest PP (Figure 7.3). This is, to some degree, consistent with the results of the ANOVA analysis, section 7.5.1. However, although the ANOVA results did not show any significant differences between EVA and Poron, Poron led to minimal pressures more frequently with each metatarsal bar position (Figure 7.3). For the EVA material condition, minimal pressures were more often achieved when combined with the base metatarsal bar position. The void material condition with each of the three metatarsal bar positions rarely achieved the lowest PP, consistent with the ANOVA analysis, section 7.5.1. These findings indicate that the optimum design was Poron as the material condition combined with either a proximal or distal metatarsal bar position.

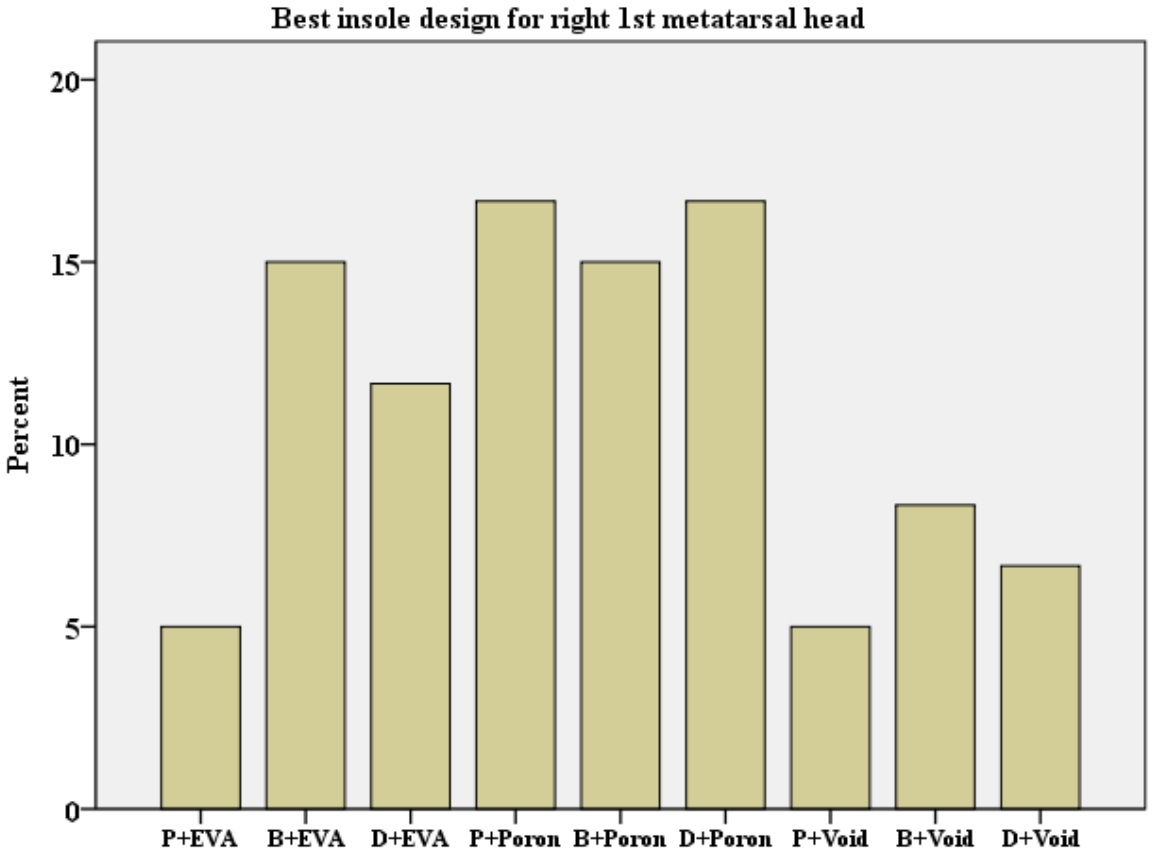

Figure 7.3: Frequency of best insole design for PP per condition for the 1st metatarsal head

7.5.3.2 Central metatarsal heads

The combination of Poron with the base metatarsal bar position most frequently lead to the lowest PP (Figure 7.4), in agreement with the results of the ANOVA analysis, section 7.5.1. Moreover, the ANOVA results showed that both EVA and Poron had a significant effect on PP, and the distribution results revealed that both material conditions led to lower pressures more often than the void condition, although Poron most frequently achieved the lowest PP (Figure 7.4). The void condition with each of the three metatarsal bar positions was rarely associated with lowest PP, consistent with the ANOVA analysis, section 7.5.1.

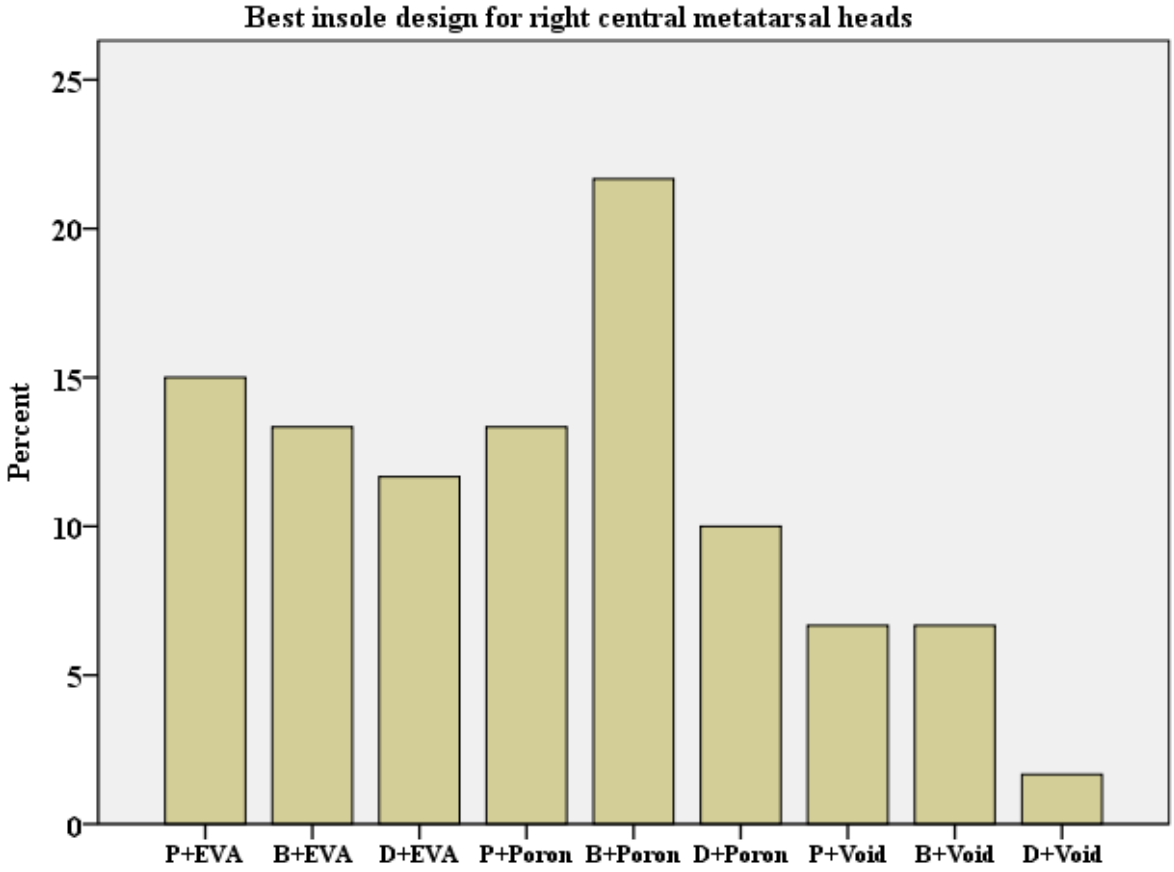

Figure 7.4: Frequency of best insole design for PP per condition for central metatarsal heads

7.5.3.3 5th metatarsal head

The combination of Poron with the base metatarsal bar position most frequently lead to the lowest PP (Figure 7.5). This is consistent with the results of the ANOVA analysis, section 7.5.1. However, although the ANOVA results showed that both EVA and Poron had a significant effect on PP, the distribution results showed that Poron led to lower pressures more frequently than EVA (Figure 7.5). The void material condition with each of the three metatarsal bar positions rarely achieved the lowest PP, in agreement with the ANOVA analysis, section 7.5.1.

Figure 7.5: Frequency of best insole design for PP per condition for the 5th metatarsal head

7.5.3.4 Hallux

Interestingly, the combination of void with the base metatarsal bar position was the design which most frequently led to the lowest PP (Figure 7.6). This is, to some degree, consistent with the results of the ANOVA analysis, section 7.5.1. For all material conditions, the distal metatarsal bar position more often led to higher pressures.

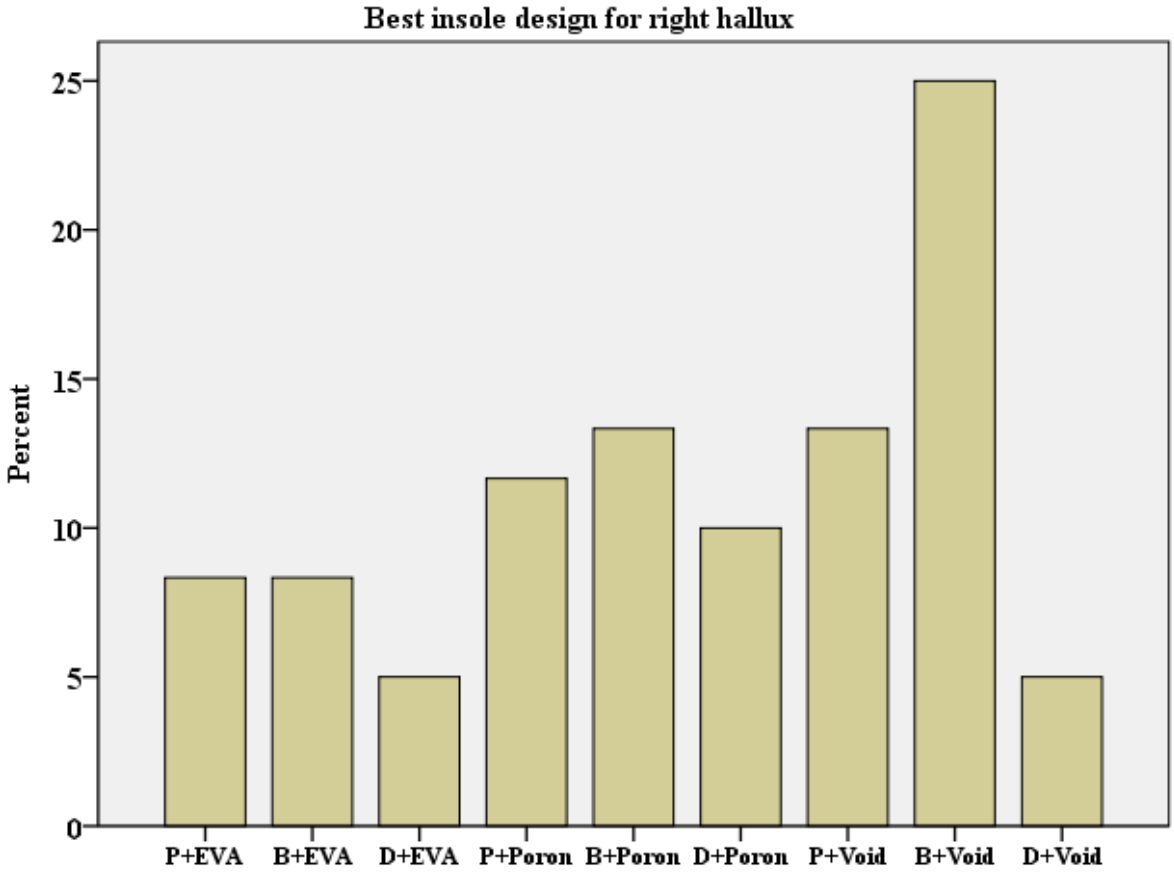

Figure 7.6: Frequency of best insole design for PP per condition for hallux

7.5.4 Comparison of the different insole designs with the control condition

One-way ANOVA with Bonferroni post-hoc correction was chosen to investigate the effect of the different insole designs compared to the control shoe.

7.5.4.1 1st metatarsal head

There was a significant difference in PP when the insole conditions were compared to the control shoe ($p < 0.001$). The Bonferroni post hoc test showed that Poron combined with all metatarsal bar positions significantly reduced PP when compared to the control shoe (Figure 7.7). Also, EVA combined with the base position was significantly different to the control shoe.

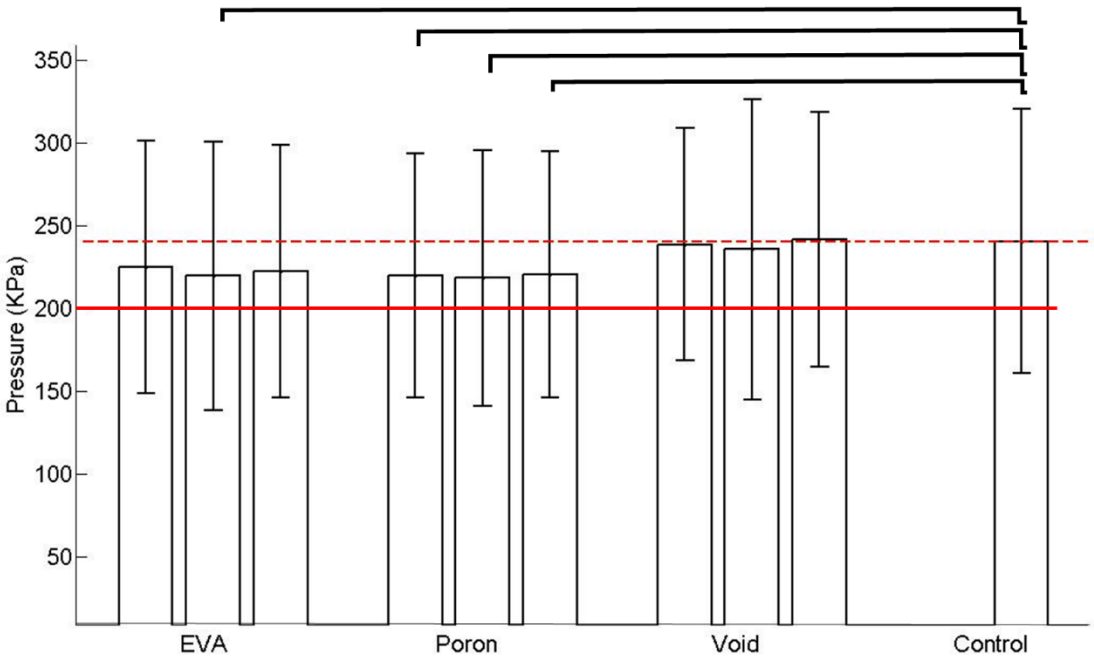

Figure 7.7: Mean PP for the three insole materials with each of the metatarsal bar positions (-2%, 0 and +2% bars from left to right) for the 1st metatarsal head. The red horizontal dotted line represents the pressure from the control shoe. The red horizontal line represents the threshold set as non-risk of ulceration (200 KPa). The black horizontal lines indicate significant differences between insole conditions ($p < 0.05$ with Bonferroni correction).

7.5.4.2 Central metatarsal head

There was a significant difference in PP when the insole conditions were compared to the control shoe ($p < 0.001$). The results of the Bonferroni post hoc test showed that both proximal and base metatarsal bar positions combined with any cushioning material (EVA and Poron) significantly reduced PP when compared to the control shoe (Figure 7.8).

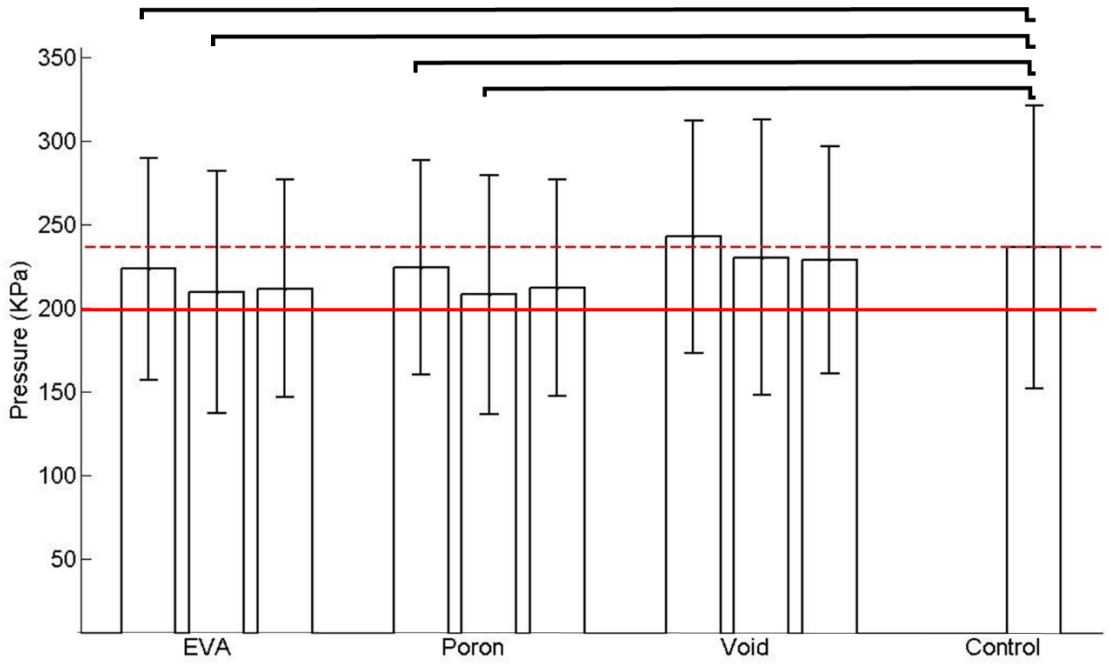

Figure 7.8: Mean PP for the three insole materials with each of the metatarsal bar positions (-2%, 0 and +2% bars from left to right) for the central metatarsal heads. The red horizontal dotted line represents the pressure from the control shoe. The red horizontal line represents the threshold set as non-risk of ulceration. The black horizontal lines indicate significant differences between insole conditions ($p < 0.05$ with Bonferroni correction).

7.5.4.3 5th metatarsal head

There was no significant difference in PP when the insole conditions were compared to the control shoe ($p = 0.066$). Interestingly, the cushioning materials did not seem to have any effect on PP. Nevertheless, all PP values for this anatomical region were observed to be under 200 KPa, which has been set as a safe threshold for ulceration.

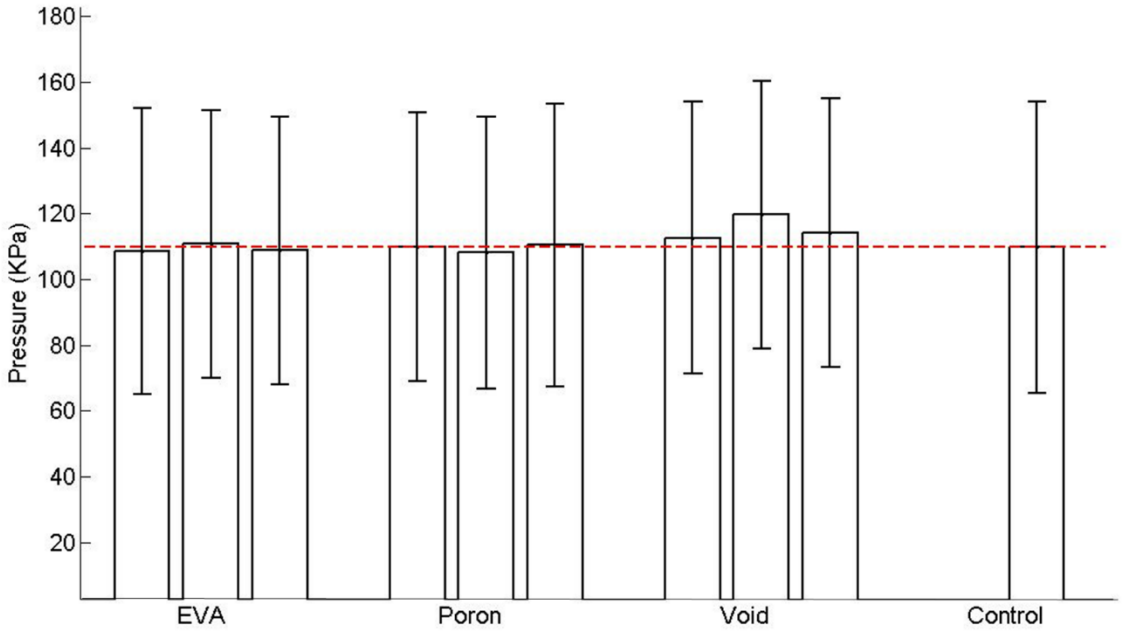

Figure 7.9: Mean PP for the three insole materials with each one of the metatarsal bar positions (-2%, 0 and +2% bars from left to right) for the right 5th metatarsal head. The red horizontal dotted line represents the pressure from the control shoe.

7.5.4.4 Hallux

There was a significant difference in PP for all the insole conditions when compared to the control shoe ($p < 0.001$). The Bonferroni post hoc test revealed that all insole conditions significantly increased PP when compared to the control shoe (Figure 7.10). This increase in PP showed a trend, being higher for the proximal metatarsal head position, followed by distal when combined with any material condition. The base metatarsal bar position seemed to increase PP the least when combined with any material condition. Interestingly, in this anatomical region, the control shoe PP was 200 KPa, but all the insole conditions increased PP to approximately 230-240 KPa.

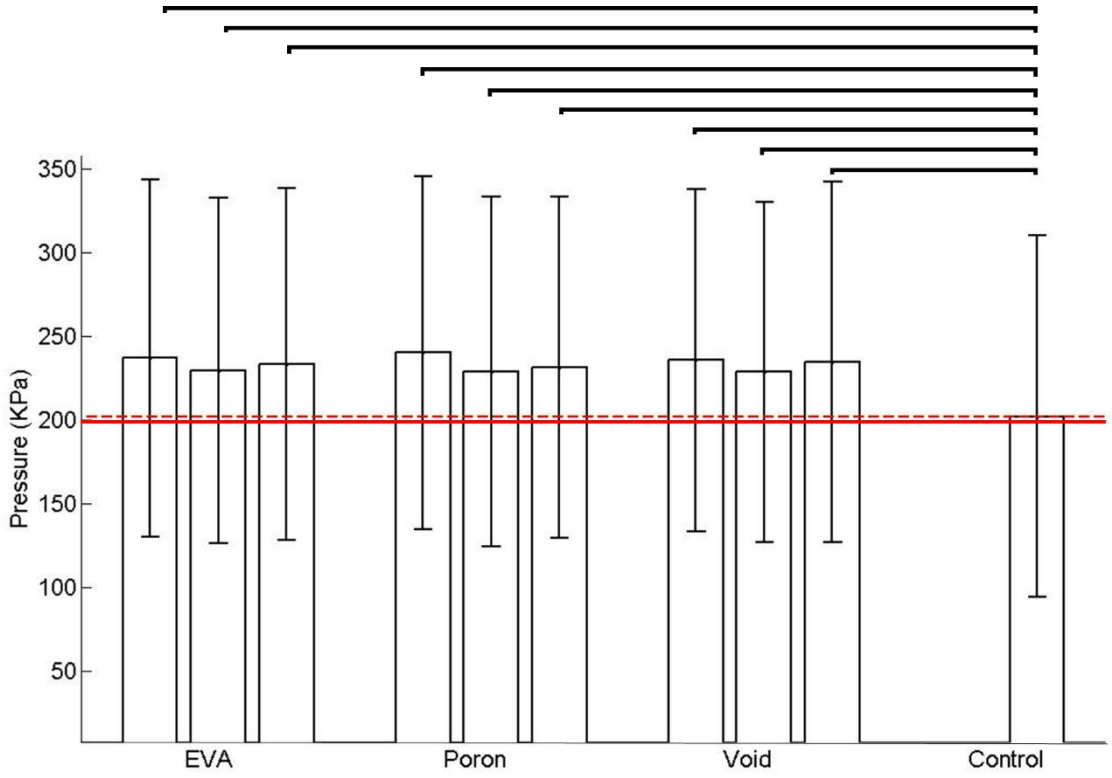

Figure 7.10: Mean PP for the three insole materials with each of the metatarsal bar positions (-2%, 0 and +2% bars from left to right) for the hallux. The red horizontal dotted line represents the pressure from the control shoe. The red horizontal line represents the threshold set as non-risk of ulceration. The black horizontal lines indicate significant differences between insole conditions ($p < 0.05$ with Bonferroni correction).

7.5.5 Comparison of best subject design with the best group design and control shoe

Descriptive statistics were used to better understand the effect of insole customisation on PP reduction. To this end, the best condition for each patient was selected and averaged across all participants. This PP was compared to the average PP for the condition that resulted in the lowest PP across the whole sample and the control shoe. This approach was selected in an attempt to gain a better understanding of the difference in PP reduction achieved with the customisations. To the best of our knowledge, this is the first time that a comparison between the effect of fully customised insoles with semi-customised and flat insoles has been made.

7.5.5.1 1st metatarsal head

The mean PP for the best insole configuration was approximately 190 KPa (Figure 7.11); lower than the 200 KPa safe threshold for ulceration (ref). For the 1st metatarsal head, the best group design was Poron combined with the proximal metatarsal bar position (Section 5.7.2.), achieving a mean PP value of 220 KPa. This result represented an increase of 30 KPa when compared to the best subject design PP. The control shoe mean PP was approximately 240 KPa, which is a mean increase of 20 KPa when compared to the best group design and 50 KPa when compared to the best subject design. An increasing trend of average PP of 20-30 KPa can be observed in Figure 7.11 when moving from fully customised insoles (best subject design) to semi-customised insoles (best group design) to standard insoles/shoes (control shoe).

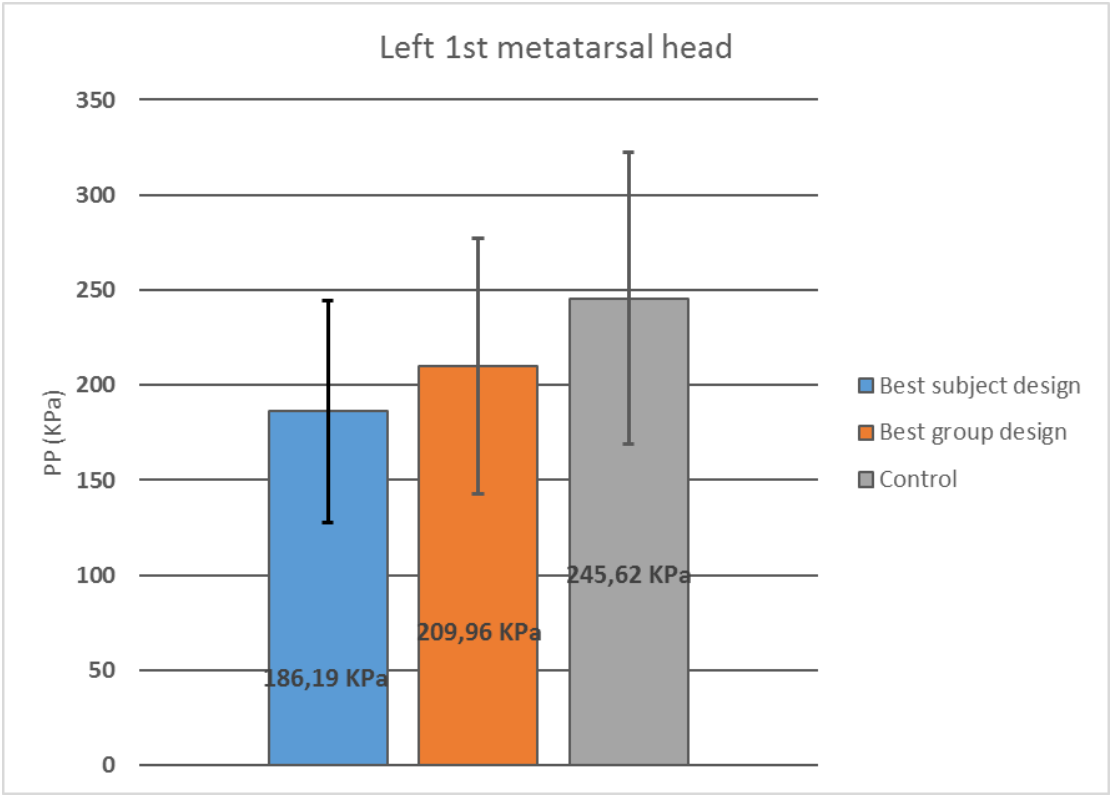

Figure 7.11: PP distributions for best subject design, best group design and control shoe

7.5.5.2 Central metatarsal heads

The best subject design PP was approximately 190 KPa under the central metatarsal heads, below the safe threshold of 200 KPa (Guldemond *et al.*, 2007). The best group design for the central metatarsal heads was the base metatarsal bar position combined with Poron, giving a mean PP value of 210 KPa, which represented an increase of 20 KPa when compared to the best subject design PP. The control shoe mean PP was approximately 240 KPa, which represented an increase of 30 KPa when compared to the best group design and 50 KPa when compared to the best subject design. Again, there was an increasing trend of 20-30 KPa in PP when moving from full customised insoles (best subject design) to semi-customised insoles (best group design) to standard insoles/shoes (control shoe).

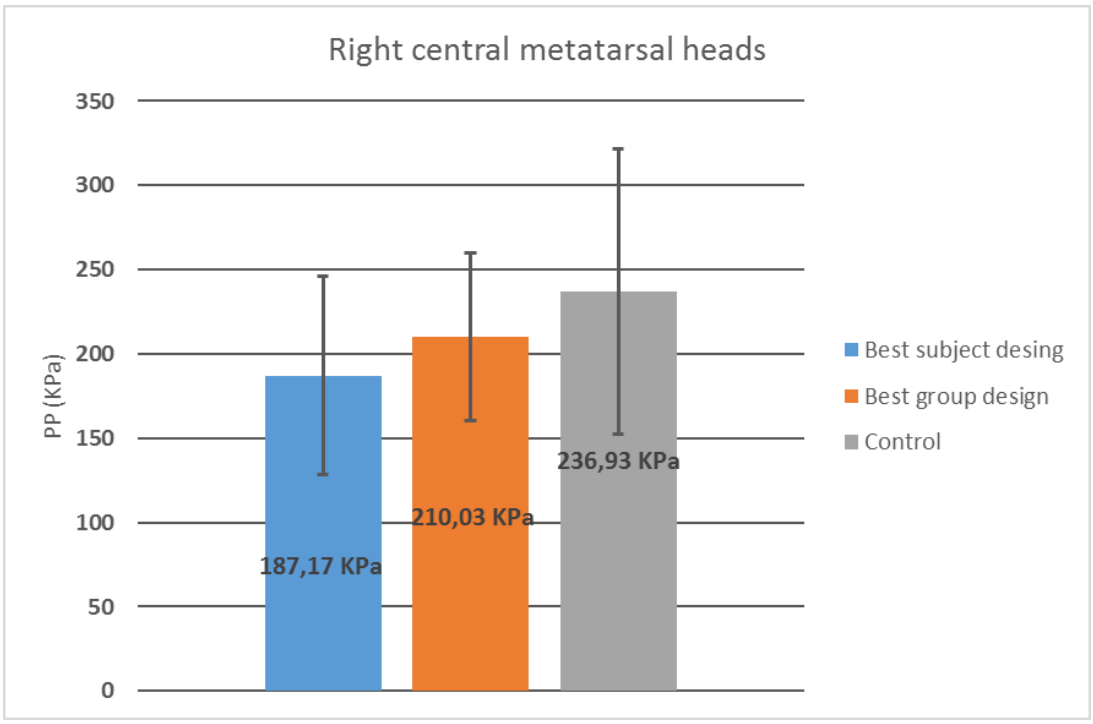

Figure 7.12: PP distributions for best subject design, best group design and control shoe

7.5.5.3 5th metatarsal head

The best subject design resulted in a PP of approximately 90 KPa under the 5th metatarsal head. For this anatomical region, the best group design was again Poron combined with the base metatarsal bar position. The mean PP value for this design combination was 110 KPa, which represented an increase of 20 KPa from the best subject design. Interestingly, the control shoe showed the same PP value as the best group design of 110 KPa. For this region, a small increase of 20 KPa in PP was observed when moving from fully customised insoles (best subject design) towards more standard approaches (both best group design and standard shoe).

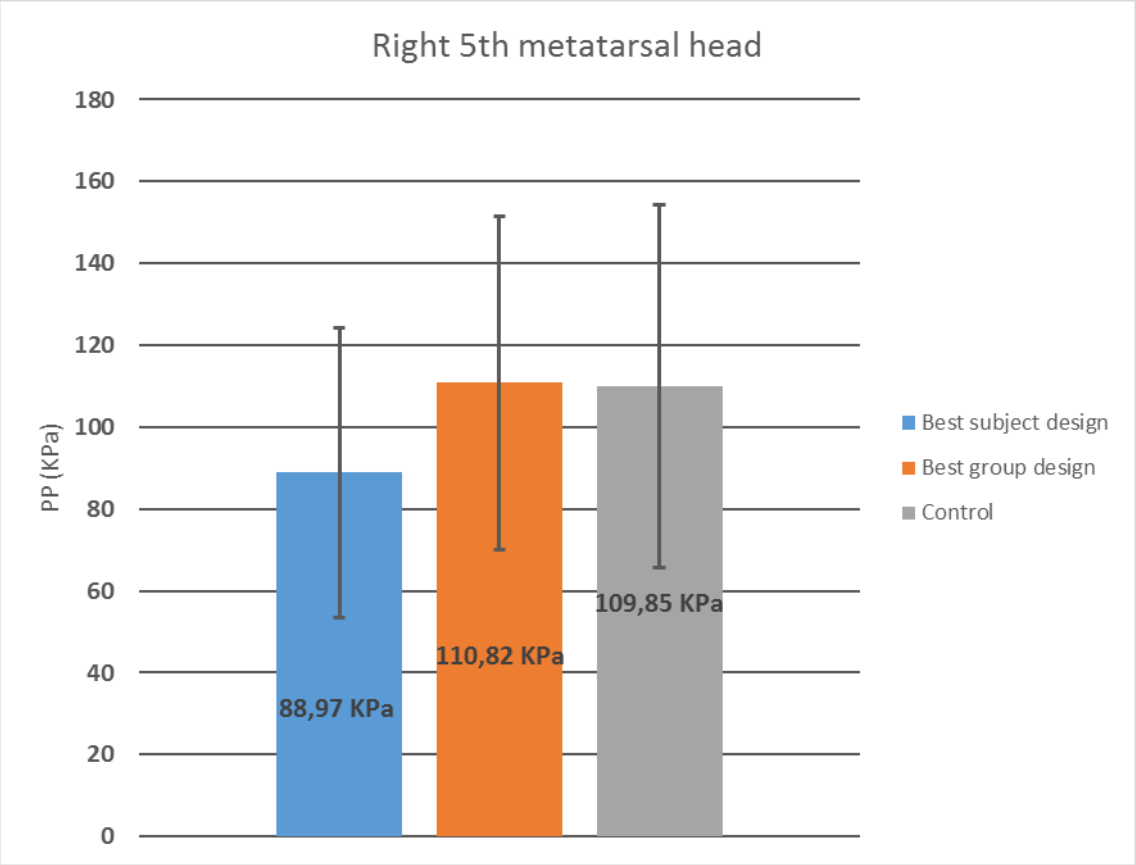

Figure 7.13: PP distributions for best subject design, best group design and control shoe

7.5.5.4 Hallux

The best subject design for the hallux resulted in a PP of approximately 220 KPa. Interestingly, this PP value was almost the same as the one obtained from the standard shoe. Moreover, the PP achieved with the best group design was approximately 230 KPa, almost 30 KPa higher than best subject design and standard shoe PP.

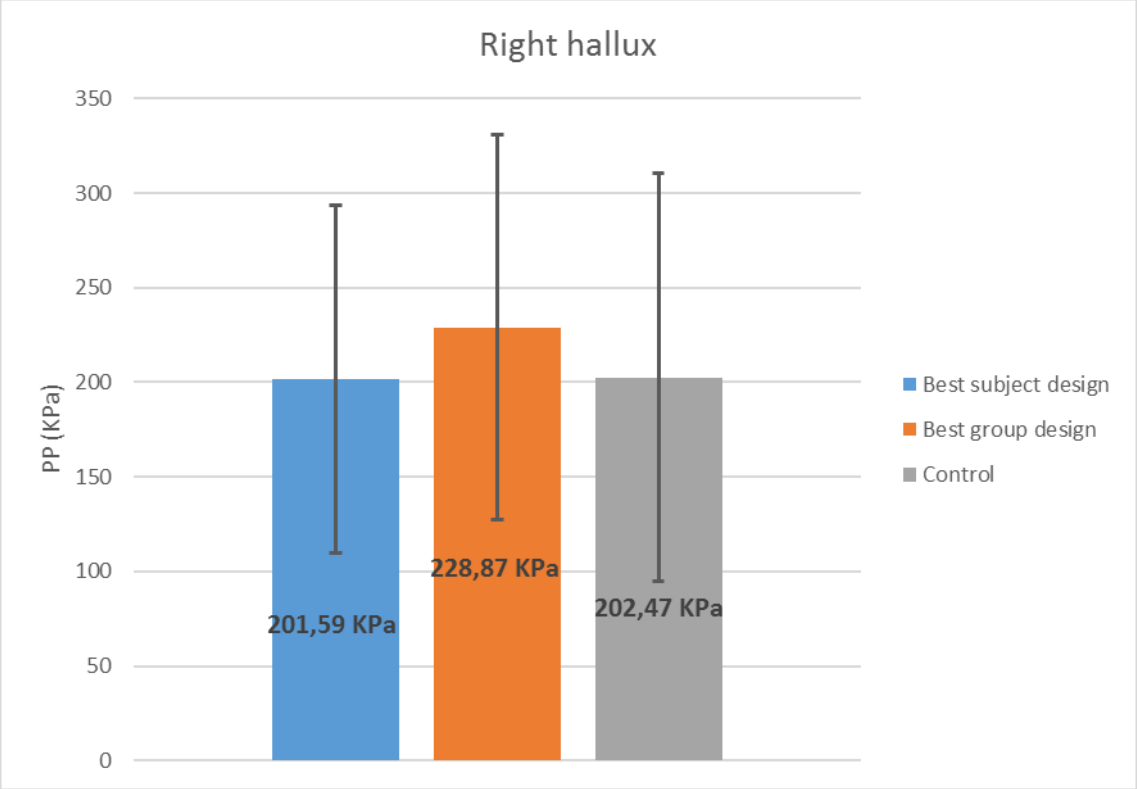

Figure 7.14: PP distributions for best subject design, best group design and control shoe

7.6 Discussion

7.6.1 Summary of the key findings

The main aim of this study was to investigate the effect of systematically varying the metatarsal bar position and the cushioning material on PP. First, the individual effect of the two separate design features (metatarsal bar position and material) was investigated and then possible interactions were analysed using a repeated measures two-way ANOVA approach. To understand the variability in the response to the insole, descriptive statistics were used to identify which insole design led to the lowest PP. The effect of each insole condition, when compared to the control shoe, was investigated using a repeated measures ANOVA. Finally, to understand the importance of customization, the main effect of the best subject design (fully customised) was compared to the best group design (semi customised) to the standard shoe using descriptive statistics. The main findings of this study were that cushioning materials are an effective approach to reducing PP under the metatarsal heads, with the exception of the hallux. The metatarsal bar position significantly influenced PP under the central metatarsal heads and the hallux, with the base position performing better than the proximal position. Interestingly, there were minimal interactions between the metatarsal bar position and cushioning material with respect to PP.

When compared to the flat insole condition (control), the results demonstrated that a combination of a cushioning material and metatarsal bar is an effective approach for reducing PP in the high-risk region of the foot. All metatarsal bar positions combined with Poron were effective in reducing PP under the first metatarsal head. A similar result was found for EVA combined with a base metatarsal bar. For the central metatarsal heads, proximal and base metatarsal bar positions combined with any cushioning material (EVA or Poron) resulted in a significant reduction in PP. Interestingly, for the 5^{th} metatarsal heads, none of the insole conditions tested was found to have a significant effect on PP. Surprisingly, for the hallux, all the insole conditions led to an increase in PP when compared to the flat insole. Overall, the insole conditions that most frequently achieved a reduction in pressure were the combination of poron with a distal metatarsal bar for the first metatarsal head, poron with the base position for both the central and 5^{th} metatarsal heads, and void with the base metatarsal bar for the hallux.

These results indicate that the combination of cushioning materials and metatarsal bars are an effective approach for reducing PP. The comparison of the different conditions to the control shoe suggests that any cushioning material combined with a base or distal metatarsal bar position would be the best choice to offload high-risk areas. However, while the PP was reduced in the metatarsal heads, the hallux experienced increased pressure, a finding which should be considered by clinicians who prescribe insoles for medium-risk patients. Moreover, although full insole customization was shown to achieve a lower PP than the shoe, the differences in pressure are large and may be the result of variability in the measurements (Chapter 6).

To date, there have been no published reports investigating the effect of the combination of cushioning material and metatarsal bar position on PP. Therefore, in order to be able to compare our results to the results published in the literature, the percentage PP reduction for the material and metatarsal bar positions when compared to the flat insole condition (sshoe) were calculated and presented in the following table:

		1st metatarsal head		**2nd-4th metatarsal head**		**5th metatarsal head**		**Hallux**	
		PP (KPa)	**%**	**PP (KPa)**	**%**	**PP (KPa)**	**%**	**PP (KPa)**	**%**
Material	**EVA**	222.69	7.56%	215.27	9.14%	109.4	0.36%	233.59	-15.37%
	Poron	219.86	8.73%	215.16	9.18%	109.5	0.27%	233.82	-15.49%
	Void	238.95	0.81%	234.29	1.11%	115.5	-5.19%	233.25	-15.21%
Metatarsal bar position	**Proximal**	228.27	5.24%	230.51	2.71%	-	-	237.88	-17.49%
	Base	224.87	6.65%	216.41	8.66%	-	-	229.32	-13.27%
	Distal	228.36	5.20%	217.81	8.01%	-	-	233.45	-15.31%
Control shoe		240.9	-	236.92	-	109.8	-	202.46	-

Table 7.9: PP for each condition and percentage PP reduction when compared to the control shoe

7.6.2 Using cushioning materials to offload plantar pressures

The use of cushioning materials in foot orthoses to help to reduce PP is a common approach adopted by practitioners. However, there is a broad range of materials available for manufacturing insoles, so the physical properties of these materials, such as the abilities of force distribution, shock absorption and durability, should be carefully considered in order to achieve the maximal therapeutic effect (Kang *et al.*, 2006). Practitioners combine materials of different densities in order to achieve the treatment goal. There are some studies that have tested the physical properties of the most commonly used materials in insole design in clinical practice. Fauli *et al.* (2008) tested different EVAs, polyurethanes, latex and polyethylenes to establish their ability to perform different applications in the insole (accommodation, energy absorption and filling application) in order to identify which was the most suitable material for each of the three applications. Low-density EVA and polyethylene were found to be the most appropriate for adaptation or accommodation due to their ability to homogenise plantar pressures. Poron was found to be the best material for a cushioning application, as it has high energy absorption. For the filling applications, high-density EVA and polyethylene were the most suitable materials to provide stability to the insole. These results agree with those obtained by Paton *et al.* (2007), who concluded that high-density EVA was the most suitable material for the filling application and Poron as a cushioning material.

The effect of insoles made of different materials on PP has also been previously investigated. Healy *et al.* (2012) tested the cushioning effect of both flat and contoured insoles made of Polyurethane (PU) and EVA of low and medium density. Subjects were tested under five conditions on two separate occasions: canvas shoe with rubber sole only, a shoe with a 3 mm flat low-density PU insole, a shoe with a 3 mm flat medium density PU insole, a shoe with a 3 mm flat low-density EVA insole and shoe with a 3 mm flat medium density EVA insole. For the second visit, they used the same protocol changing the flat insoles for contoured ones of the same material. Their results show that both low-density materials achieve a lower PP than the control shoe, which agrees with our results. Interestingly, they also found an increase in PP under the hallux for customised insoles. However, despite the similar conclusions, the results are only comparable to a certain extent, given that they used the cushioning material throughout the whole insole rather than combining different density materials as in our study.

The effect of combining two materials in an insole was investigated by Actis *et al.* (2008). In this study, they first produced patient-specific finite element models to study the influence of the insole design on PP under the metatarsal heads. Based on the results obtained from this model, they modified a customised insole for each one of the two participants, one with a history of forefoot pain and one with diabetes and neuropathy. A 4 mm cylinder of Poron was located under the PP point and three to four cylinders both proximally and distally to it. Four different insoles were manufactured for each participant: customised 10 mm thick plastazote, customised plastazote with poron cylinder inserts under the areas of PP customised plastazote with Poron plugs were placed throughout the entire forefoot region and a customised plastazote with a single 7 mm thick sheet of Poron in the forefoot region. They found that all the insoles with cushioning material produced a decrease in PP under the central forefoot of 13% when compared to the insole with no material, which aligns with the 10% achieved in this region with cushioning materials in the present study. Interestingly, they also found a small increase in PP under the hallux, similar to the results obtained previously (Healy *et al.*, 2012) and in line with our results. In addition, they found that insoles with cushioning material achieved less PP reduction in the subject with diabetes compared to the subject without this condition. This difference in the insole effect between subjects highlights the importance of considering the study subjects when interpreting papers and applying interventions for patients with diabetes.

It has been shown that cushioning materials are effective in improving the offloading effect of insoles. Moreover, the combination of different density materials appears to be the best approach to achieve the highest PP reduction. However, given the wide range of materials available for podiatric practice, the choice of materials requires careful consideration. Nevertheless, there are other insole design approaches to reduce PP apart from cushioning materials. The most popular insole addition to offloading forefoot PP is the metatarsal bar (Hayda *et al.*, 1994, Lee *et al.*, 2014). However, there is some controversy in exactly where the metatarsal bar should be positioned to achieve maximal PP reduction.

7.6.3 Optimal positioning of the metatarsal bar for reducing plantar pressures

Metatarsal bars and pads are one of the most commonly used additions by podiatrists to reduce PP. There are a number of publications investigating their effect on PP with very different approaches. Holmes&Timmerman (1990) used barefoot plantar pressure data to locate the areas of higher pressure in the metatarsal heads. Metatarsal pads were then fixed to the participant's plantar aspect of the foot just proximally to the metatarsal heads. Barefoot plantar pressures were collected with the metatarsal pads fixed to the foot sole. They found a reduction in PP on all of the areas studied while wearing the metatarsal pad, with the exception of the hallux. These results are in line with the present study, achieving lower PP under the metatarsal heads, but with a small increase under the hallux. However, their choice of collecting barefoot plantar pressure may not be the best approach as it may not give an accurate indication of the in-shoe plantar pressure. Moreover, they used standard metatarsal pads, which are not the best choice given the wide range of materials, shapes and sizes available. This makes them unsuitable for all subjects and not comparable to other studies given their different physical properties.

Hsi *et al.* (2005) investigated the optimum position of the metatarsal pad to reduce PP. They recruited ten male participants with a history of metatarsalgia but with no other foot disorders. They taped Novel Pliance to the sole of the foot of each participant to ensure that the same anatomic region of the foot was in contact with the same sensors. Barefoot plantar pressure was measured and the metatarsal heads were located on the sensors based on PP. A metatarsal pad was then taped two sensors proximal to the metatarsal heads on the Novel Pliance. The metatarsal pad was moved 4.4 mm (one sensor) distally twice from the first placement to just proximal to the metatarsal heads and distal to the metatarsal heads. They found that the optimum metatarsal pad position to be just proximal to the metatarsal heads. This is in agreement with our work that found that the base position was the most efficient along with a distal position. However, this study uses barefoot plantar pressures which are not comparable to in-shoe plantar pressures. Also, taping the metatarsal pad to the foot may not be the most appropriate approach. Moreover, they used standard metatarsal pads which are not the most appropriate choice and are not comparable to other studies given the most likely different

physical properties. Koenraadt *et al.* (2012) followed the approach of Hsi *et al.* (2005), locating metatarsal pads just proximal to the metatarsal heads. This was performed by an experienced physical therapist using double sided tape, rather than using PP data. They also found a significant reduction under the metatarsal heads with a metatarsal pad. Our results agree with theirs, but the limitations of their study are very similar to those of Hsi *et al.* (2005), which is a more inaccurate approach to metatarsal pad positioning.

Kang *et al.* (2006) aimed to understand the effect of metatarsal pads on PP; they investigated the effect that the metatarsal pad had on PP when fixed to the shoe insole. To this end, they recruited a total of 13 patients with a history of forefoot pain. An experienced physiatrist located the metatarsal pad just proximally to the second metatarsal head. They did not standardise the shoe and collected pressures with and without the metatarsal pad. A significant PP reduction of approximately 10% was achieved with the metatarsal pad when compared to the shoe on its own. However, although these results agree with ours, the approach chosen to locate the metatarsal bar may have been inconsistent. Moreover, they fixed the metatarsal pad to the shoe rather than using a contoured insole and did not standardise the shoe. Additionally, they allowed a 15% speed deviation which may have influenced plantar pressure behaviour. Furthermore, they used standard metatarsal pads, which are not suitable for all subjects and not comparable to other studies given the most likely different physical properties. Finally, they did not standardise the shoe, which makes the comparison between subjects more difficult given the different characteristics of the shoes used.

Lee *et al.* (2014) also investigated the effect of metatarsal pads and bars in PP. To this end, they recruited a total of 37 participants older than 65years of age to measure plantar pressures with a Novel Pedar in-shoe system. Five different conditions were tested: extra-deep shoe, metatarsal pad 10 mm proximal to metatarsal heads, metatarsal pad 5 mm distal to metatarsal heads, metatarsal bar 10 mm proximal to metatarsal heads and plantar cover. The metatarsal heads were located by palpation and the centre of the most distal aspect of each metatarsal head was marked on the plantar surface of the foot using a pen. This ink mark was then transferred onto a cardboard template where the additions were fixed with double sided tape. Their results showed that all the different additions used significantly reduced PP when compared to the control shoe. The most efficient condition was the metatarsal pad located distally from the metatarsal heads with

a reduction of 17% in PP. They obtained the highest offloading with the distal position similar to our findings but achieved a higher PP reduction than in this study (10%). However, they studied the whole forefoot as an anatomical region rather than dividing it into different regions of interest. This masking approach varies significantly to ours; hence, the results are not comparable. Moreover, the location of the metatarsal additions may not be very accurate and should have been based on pressure rather than marking anatomical prominences and transferring them to a cardboard. Additionally, a cardboard template may not be the most appropriate material to help to reduce PP. Furthermore, they used standard metatarsal pads which are not suitable for all subjects and not comparable to other studies given the most likely different physical properties.

Brodtkorb *et al.* (2008) investigated the effect of the metatarsal bar position in 22 healthy young subjects with asymptomatic feet by measuring static barefoot plantar pressures. The metatarsal pad was fixed on the Pedar insole just proximal to metatarsal heads with the same approach used by Lee *et al.* (2014). The subject was then asked to stand on one leg while maintaining their balance on top of the Novel Pedar insole and the barefoot plantar pressure was measured. They moved the metatarsal pad 5 mm distally on six different occasions and barefoot plantar pressure was collected following the same protocol. They found that the metatarsal pad significantly reduced PP, but there were no significant differences between the positions of the metatarsal pad while moving it distally. This is in agreement with our results, which did not find differences between the base and the distal metatarsal bar positions, but both were significantly more effective than the proximal position. However, the protocol followed by this study is not the most appropriate for several reasons. Barefoot plantar pressures are not comparable to in-shoe plantar pressures. Moreover, they collected static plantar pressures which are significantly different to dynamic plantar pressures. Finally, they measured the pressure while the subjects maintained their balance standing on one foot, which is not comparable to normal gait or even bipedal stance.

The effect of the combination of a metatarsal pad with an insole was studied by Mueller *et al.* (2006) in 20 subjects with diabetes and neuropathy. The participants were provided with extra-deep shoes and customised insoles with standard metatarsal pads made of cork attached. The metatarsal pad was located 10 mm proximal from the metatarsal heads by a certified orthotist. In-shoe plantar pressure was then measured in

three different conditions: shoe only, customised insole and customised insole with a metatarsal pad. They concluded that the addition of the metatarsal pad to a customised insole had a substantial and additive effect on reducing PP by 19% to 24% under the metatarsal heads when compared to the control shoe. They achieved higher PP reductions than other studies previously discussed in this section by using customised insoles instead of flat insoles or metatarsal pads on their own. These results are in line with ours, but they achieved a higher PP reduction. However, an orthotist placed the metatarsal pad by locating the metatarsal heads on the positive mould of the foot. This is not an accurate approach to locating the addition. Moreover, they taped the pressure sensor to the foot and secured it with a sock, which might influence the data collection. Additionally, they used a standard metatarsal pad which might not have the same effect on subjects with different foot sizes.

Hodge *et al.* (1999) compared the effect of metatarsal pads on contoured insoles and customised insoles on PP. They recruited 12 participants with rheumatoid arthritis and a history of forefoot pain. Plantar pressures were collected with a Novel Pedar in-shoe device on a standard contoured insole and a custom made insole, both made of EVA. A standard metatarsal dome and a standard metatarsal bar were located proximal to the metatarsal heads by palpation and fixed to the insoles with double sided tape. Five different conditions were tested: shoe only, contoured insole with metatarsal pad, contoured insole with metatarsal bar, customised insole with metatarsal pad and customised insole with metatarsal bar. Their results showed that customised insoles with both a metatarsal pad and metatarsal bar were the most efficient to reduce PP. These results agree with our results, showing that customised insoles with metatarsal additions are effective. However, they used standard metatarsal pads and domes which may not be suitable for all participants for size and material properties. Additionally, the positioning of the metatarsal additions was made by a practitioner, which is not as accurate as using pressure data.

Hastings *et al.* (2007) studied the effect of different metatarsal bar positions on customised insoles in PP. To this end, 20 subjects with diabetes and neuropathy were recruited and customised insoles were manufactured from a foam box. Subjects were tested in three conditions: shoe only, customised insole with proximal metatarsal pad and customised insole with distal metatarsal pad. The metatarsal pad was made of cork and

located by an orthotist, who drew a line identifying the metatarsal heads. The distal metatarsal pad location was just distal to the line for the metatarsal heads and the proximal, 10 mm proximal to this line. Interestingly, they found consistent PP reduction when the metatarsal pad was located 6 to 11 mm proximal to the metatarsal heads. This finding is contrary to most of the literature discussed in this chapter, as well as our results, which show that base and distal positions of the metatarsal bar achieve higher PP reductions than proximal.

The effect on PP of different insole configurations changing the arch and the metatarsal pad characteristics were studied by Guldemond *et al.* (2007). They collected pressure data from 20 male patients with diabetes and neuropathy who had elevated barefoot plantar pressures. Basic customised insoles were manufactured for each participant and additions for the arch and the metatarsal pad were added in different combinations to investigate their offloading effect. Arch height could be modified and the dome was positioned 5 mm proximal from the metatarsal heads based on a pressure sheet footprint. They found that the main PP reductions of approximately 15% were achieved by the metatarsal dome and the extra arch support, slightly higher than achieved in our study. This finding highlights the importance of the arch support to reduce pressure, which a customised insole provides. Their results agree with ours, achieving offloading with a customised insole with a metatarsal pad just behind PP. However, the extra arch support was reported as being uncomfortable by most participants and a special extra-deep shoe would be required to accommodate this type of insole. On the contrary, our insole design focused on being suitable for most normal footwear.

The effect of flat insoles and customised insoles with a metatarsal bar in PP was performed byBus *et al.* (2004). They collected data from 20 subjects with diabetes and neuropathy. The used a standard flat insole and a fully customised insole manufactured with a CAD-CAM system, based on plantar pressures and footprints sent to a trained orthopaedic shoemaker. Their results showed a decrease in PP of 16% under all metatarsal heads when comparing the customised insole to the flat insole, which is in agreement with our results. The use of a CAD-CAM system to manufacture these insoles increased the accuracy and repeatability of the process. However, the customised insoles were very thick, which might explain the slightly higher PP reductions they achieved and would

require special extra-deep therapeutic shoes. Our insole design, on the other hand, achieved slightly lower offloading but would fit in most normal footwear.

All the studies discussed above show that the combination of a cushioning material with a metatarsal bar is an effective approach for PP reduction. Moreover, this plantar pressure reduction increases when these additions are combined with a customised insole rather than flat insoles or the shoe. Customised insoles have been shown to be effective in reducing PP, with those designed and manufactured with a CAD-CAM system being the most efficient. However, all the studies presented have used standard metatarsal bars and pads rather than customising them based on plantar pressures. Only one study by Patry *et al.*, 2013Owings *et al.* (2008) used fully customised insoles with fully customised metatarsal bars based on both foot shape and plantar pressures.

In their study, Owings *et al.* (2008) recruited a total of 22 subjects with diabetes and neuropathy with a barefoot PP higher than 750 KPa under the forefoot. This barefoot plantar pressure was measured from the first step taken over the Novel Emed pressure platform. Foam boxes were sent to three different orthotic supply companies, but only one was also supplied with plantar pressure data as well. Therefore, they obtained two different customised insoles without pressure data: the first was made of polypropylene with a plastazote top cover, and the second was made of EVA with a plastazote top cover. The third pair of insoles were designed and manufactured with a CAD-CAM system. The software adapted a template insole to the subject's foot shape and an automated design algorithm identified a pressure contour along with a metatarsal bar. Furthermore, a 3 mm deep void was created under regions of excessive PP (> 1,000 KPa). Subjects were tested with each one of the insoles inside an extra-deep shoe with a normal sole and inside the same shoe with a rocker sole. There was a total of 7 conditions using the shoe with a normal sole as the control condition with its stock insole inside. In-shoe plantar pressures were collected while walking at their self-speed and a ±10% deviation was allowed.

Owings *et al.* (2008) found that the fully customised insole with a customised metatarsal bar was the optimum design to offload PP. Furthermore, they found that the combination of this insole design with a rocker shoe increased PP reduction, 37% compared to the other insole designs with the rocker shoe. Our results are similar to theirs, although they achieved a higher offloading with the flexible shoe. This is most likely

because they used very thick insoles that required special extra-deep therapeutic shoes, whereas we aimed to design insoles that would fit in most normal footwear. This choice was motivated by previous studies which have shown that participants are often unwilling to change their normal shoes (Williams *et al.*, 2010). In addition, they only recruited subjects with very high PP, while we did not use pressure as inclusion criteria. Moreover, they only analysed plantar pressure for the first step taken, which is not representative of the normal gait pressures. Finally, although they used fully customised insoles, they did not add any cushioning material in order to increase the PP reduction.

7.7 Limitations of the study

This study has a number of limitations. The first is the difficulty in interpreting small changes in the plantar pressure data because of the relatively high level of variability observed (observed in Chapter 6). It is likely that this variability results from the participants, rather than the measurement system, as all participants were elderly with diabetes and neuropathy. Nevertheless, this level of variability may impact on the data and the potential to draw a conclusion on an individual basis. However, the primary objective of this Chapter was to understand the average group effect of the two different insole design features. As there is no reason that the variability would lead to a systematic offset, the average pressure responses across the 60 participants should have removed the random variability which results from gait variability. Thus, the study findings are likely to give an accurate insight into the mean effect of changing both the metatarsal bar position and material. However, the large standard deviations which may, to some degree, be the result of within-subject variability in gait.

Self-selected walking speed for each subject was used in this study by calculating an average from five separate preliminary walking trials. All subsequent trials were then accepted if the walking speed was within a ±10% tolerance. Although for many participants it was possible to work to ±5% tolerance, the participants with diabetes were often not able to repeatedly walk within this tightly controlled speed range. Therefore, speed tolerance was increased to ±10% to ensure participants could complete the testing before becoming fatigued. However, research has shown that walking speed can influence plantar pressures (Segal *et al.*, 2004). Therefore, it is possible that some of the variability in the measurements could be attributed to differences in walking speed between the two

days. Nonetheless, a tolerance of 10% was adopted to ensure data could be collected from every participant.

Another possible limitation of this study is that the subjects were without a history of ulceration, such patients are likely to have lower PP than subjects who have had an ulcer previously. Nevertheless, the population in this study would still be considered at risk of suffering an ulcer at some stage. Therefore, this study is still one of the first to provide insight into customised insole design for patients at risk of developing foot ulceration.

7.7.1 Clinical implications & conclusions

The results obtained in this study show that the combination of a cushioning material with a metatarsal bar is an effective approach for reducing PP under the metatarsal heads. Specifically, cushioning materials led to significantly lower PP under all metatarsal heads when compared to the void condition. Interestingly, there were no significant differences in the effect on PP between both cushioning materials. Regarding the metatarsal bar position, both base and distal metatarsal bar resulted in lower PP under the hallux and central metatarsal heads. For the rest of the anatomical regions, the metatarsal bar position had no significant effect on PP. Accordingly, a base or distal metatarsal bar with a cushioning material should be prescribed to offload metatarsal bars and be combined with a void for the hallux.

For all anatomical regions, the base and distal metatarsal bar positions most frequently resulted in a lower PP. Regarding the cushioning materials, Poron achieved the highest PP reductions under metatarsal heads. Interestingly, under the hallux, the void was the best approach to significantly reduce PP. Accordingly, the conditions that most frequently led to a minimal PP under the metatarsal heads were the base and distal metatarsal bars combined with Poron and combined with a void for the hallux.

Compared to the control shoe, any cushioning material combined with a metatarsal base or distal metatarsal bar achieved PP reduction under the 1st and central metatarsal heads. Interestingly, no insole design significantly reduced PP for the 5th metatarsal head, PP increased for all insole conditions tested. Accordingly, we can conclude that the combination of a customised metatarsal bar and cushioning material is

an effective approach for reducing PP under the metatarsal heads, but an increase of under the hallux should be expected.

The PP distribution with the best subject design was compared to that achieved by the best group design and the control shoe to help understand the importance of customization (Section 7.5.4). The lowest PP distribution under all anatomical regions, except the hallux, was achieved by the best subject design. Also, PP distribution with the best subject design remained below 200 KPa for all regions, which might dramatically reduce the risk of ulceration. The results from this study indicate that new technologies provide the opportunity for a quantitative customised prescription, which itself has also been shown to be effective in reducing PP.

8 Identifying variables which may affect an individual's response to insole design

8.1 Background

Plantar pressure during walking is influenced by multiple factors, for example, foot structure can affect peak pressure (Ledoux *et al.*, 2005, Guiotto *et al.*, 2013). Foot deformity has also been found to be a strong predictor of PP. Indeed, Mueller *et al*. (2003) found the presence of hammer-toe on the hallux predicts peak pressure under the metatarsal heads and hallux. In addition, Barn *et al*. (2015) found evidence that the presence of a local deformity is a major contributing factor to barefoot dynamic pressures in high-risk diabetic patients. Furthermore, a strong inverse relationship between plantar tissue thickness and dynamic foot pressure has been reported (Abouaesha *et al.*, 2001). Moreover, limited joint mobility, produced by peripheral neuropathy, contributes to increasing plantar pressure by limiting foot flexibility and restraining the forward progression of body weight during the stance phase of gait (Fernando *et al.*, 1991, Fernando *et al.*, 2013). Taken together, these studies show that a range of different structural factors can have a strong influence on plantar pressure during walking.

In addition to structural factors, biomechanical factors also have the potential to influence plantar pressure during walking. For example, Morag&Cavanagh (1999) found that PP under the 1st metatarsophalangeal joint (MPJ) and hallux pressures were highly influenced by the 1st MPJ range of movement (ROM). Payne *et al.* (2001) also showed that the 1st MPJ ROM is important in determining pressures under the hallux. In another study, Fernando *et al*. (2013) found that patients with neuropathy walked slower and had a reduced stride length when compared to non-neuropathic patients with diabetes and healthy subjects. They also found that patients with neuropathy spent a longer period of time in the stance phase compared to the non-neuropathic subjects with diabetes. Taken together, these findings illustrate that plantar pressure during walking can be influenced by biomechanical factors.

To date, there have been a number of studies which have sought to understand whether structural or biomechanical factors may predict plantar pressure patterns during walking. However, it is possible that such factors may also dictate the way an individual responds to a particular insole design. For example, a patient with limited 1st MPJ range of movement may experience decreases in pressure under the forefoot when wearing an insole design incorporating a distally positioned metatarsal bar but minimal changes in pressure with another insole design. Clearly, such information is of enormous value to clinicians who regularly prescribe insoles designed to decrease pressure in patients with risk of ulceration. However, to date, there have been no studies which have attempted to identify the factors which could be used to predict individual responses to a range of different insole designs. Such an understanding would lead to effective clinical decision tools which could be used to target orthotic interventions more appropriately. Therefore, the aim of this chapter was to develop an understanding of the characteristics that may influence individual response to different insole designs.

8.2 Research questions

- Which characteristics influence in-shoe PP reduction?
- Which characteristics influence in-shoe PP increase?
- Which characteristics could be used to inform the choice of insole design?

8.3 Study design

Different biomechanical, clinical and demographic characteristics were recorded for each subject along with in-shoe pressure data in each of the insole conditions (Section 8.4). Hypotheses relating to each characteristic were tested by analysing whether the characteristic influenced the individual response to each customised insole design. To this end, different subject's characteristics that may have an impact on PP behaviour were identified and recorded during the data collection. These characteristics were selected on the basis of their association with PP in previous studies, such as different joint ROM, tissue stiffness or foot and ankle biomechanics. Further justification for each of these characteristics is given in section 8.4.

8.4 Experimental procedure

For this study, the same sample as for the previous study (n = 60) was used so see Chapter 5 for details of the inclusion/exclusion criteria and screening. Each participant was required to visit the Human Performance Laboratory in the Brian Blatchford building at the University of Salford on two separate occasions.

8.4.1 First visit

Initially, all participants underwent a neuropathy screening in a lying position to confirm their suitability to participate in the study (described in Chapter 5). Once the diagnosis of neuropathy was confirmed and the participant deemed eligible for the study, all the subject's characteristics that may influence their response to insole design were collected, including BMI, tissue stiffness on five different regions of the plantar aspect of the foot, arch height, ankle, 1st MPJ and subtalar joints ROM, and foot and ankle joints velocities. The protocol for this data collection is detailed below.

8.4.1.1 Foot characterisation

A range of simple clinical measurements was used to characterise foot morphology, joint movement/mobility, skin tissue stiffness and foot and ankle motion as described below with a rationale for inclusion in the study.

Arch height: Foot structure has been shown to be a predictor of plantar pressure (Barn *et al.*, 2015). One of the most common foot deformities is increased arch height (cavus foot), which is also common among patients with diabetes (Ledoux *et al.*, 2005). A greater arch height results in a smaller contact area of the foot with the ground while walking, which causes a redistribution of peak pressures across the foot. Chuckpaiwong *et al.* (2008) found that PP was significantly decreased in the low arch foot when compared to the normal foot. For this study, arch height was recorded as the distance from the navicular to the floor with the participant standing barefoot; this distance was measured using a tape measure for both feet (Menz&Morris, 2006).

Joint mobility was tested as subjects with diabetes often have ROM limitations in their foot joints (Guiotto *et al.*, 2013). The limited dorsiflexion and subtalar ROM

restrict the foot's ability to absorb shock and transverse rotation, increasing plantar pressures (Rao *et al.*, 2010), therefore increasing the risk of plantar ulceration in the foot with a lack of sensitivity (Fernando *et al.*, 1991). In addition to ankle and subtalar joints, limitation on the 1st MPJ ROM has been shown to increase pressures, and consequently, the risk of ulceration (Viswanathan *et al.*, 2003, Viswanathan *et al.*, 2008). Accordingly, the mobility of these three joints was measured using a goniometer. For these measurements, the participant was asked to lie down on a bed, to relax and to not contribute to the movement. A further rationale for each of the joints recorded and the protocol followed are as follows:

- **Subtalar joint mobility:** the subtalar joint has been documented to have reduced passive mobility in subjects with diabetes (Fernando *et al.*, 1991), which may result in a reduced calcaneal eversion and inversion ROM during walking. This loss of mobility may be associated with a decrease in forefoot mobility because the subtalar joint is believed to ''unlock'' the midfoot to allow greater mobility (Blackwood *et al.*, 2005). Rao *et al.* (2007) found decreased eversion ROM in subjects with diabetes and subsequently, associations between decreased subtalar ROM and PP increase on the medial forefoot (Rao *et al.*, 2010).

  In this study, the subtalar ROM was recorded by a goniometer placed on the central axis of the leg and calcaneus, positioning the fulcrum on the Achilles' tendon. The leg-heel angle in the relaxed position was recorded and then, from this neutral position, a complete inversion movement was performed on the joint and the reading on the goniometer was recorded. The joint was brought back to neutral position and a complete eversion movement was performed, with the goniometer measurement recorded as inversion and eversion.

- **1st MPJ mobility**: the 1st MPJ is one of the most common joints of the foot affected by neuropathy (Guiotto *et al.*, 2013). Birke *et al.* (1995) reported that when this joint becomes restricted, PP under the 1st metatarsal head rises in patients with diabetes. However, Bryant *et al.* (1999) reported that peak pressure under the 1st MPJ was significantly reduced in subjects with hallux limitus compared to controls. There is controversy about the relationship between the 1st MPJ ROM and PP behaviour, but several authors have concluded that it acts as a

PP predictor (Payne *et al.*, 2001, Menz&Morris, 2006, Turner *et al.*, 2007, Rao *et al.*, 2010).

In this study, the ROM of this joint was recorded by placing the goniometer fulcrum on the joint, positioning one arm along the hallux, and the other arm along the 1st metatarsal up to the navicular. A complete dorsal flexion of the joint was performed and recorded as 1st MPJ ROM.

- **Ankle joint mobility:** the ankle is the joint most commonly affected by neuropathy (Guiotto *et al.*, 2013). The lack of mobility has been associated with high PP and PTI under the forefoot (Zimny *et al.*, 2004). Moreover, a lack of mobility on the ankle can lead to an elevated time-dependent load on the forefoot (Fernando *et al.*, 1991), a variable which has previously been found to be one of the predictors of plantar pressure (Payne *et al.*, 2001).

  In this study, the ROM of this joint was recorded by positioning the goniometer fulcrum on the external malleoli, with one arm following the fibula and the other arm going down to the 5th metatarsal head, then a complete dorsal flexion of the foot was performed

Plantar tissue stiffness properties were collected as they are believed to play a fundamental role in PP cushioning during gait. Plantar soft tissues, in particular on the forefoot and heel regions, are specially structured to provide cushioning and shock absorption during walking. Stiffening of these tissues is associated with diabetic neuropathy and has been found to significantly increase the plantar pressure and internal stress. Therefore, it has been proposed to be an additional predictive factor of ulcer development (Pai&Ledoux, 2010, Sun *et al.*, 2011, Periyasamy *et al.*, 2012, Patry *et al.*, 2013). Durometers are used for characterising material stiffness but have also been shown to be reliable to characterise tissue stiffness (Piaggesi *et al.*, 1999).

In this study, a durometer was used to measure tissue stiffness at five different locations on the plantar foot to characterise the tissue stiffness properties. These areas were the 1st, 3rd and 5th metatarsal heads, arch and heel. To test the skin stiffness, the durometer was located in the test area and pressed against it perpendicularly (Figure 8.1). On the metatarsal heads, a plantarflexion of the joint was performed to avoid its dorsiflexion while being pressed and to reproduce the movement on the push-off phase of the gait where the highest PP occurred.

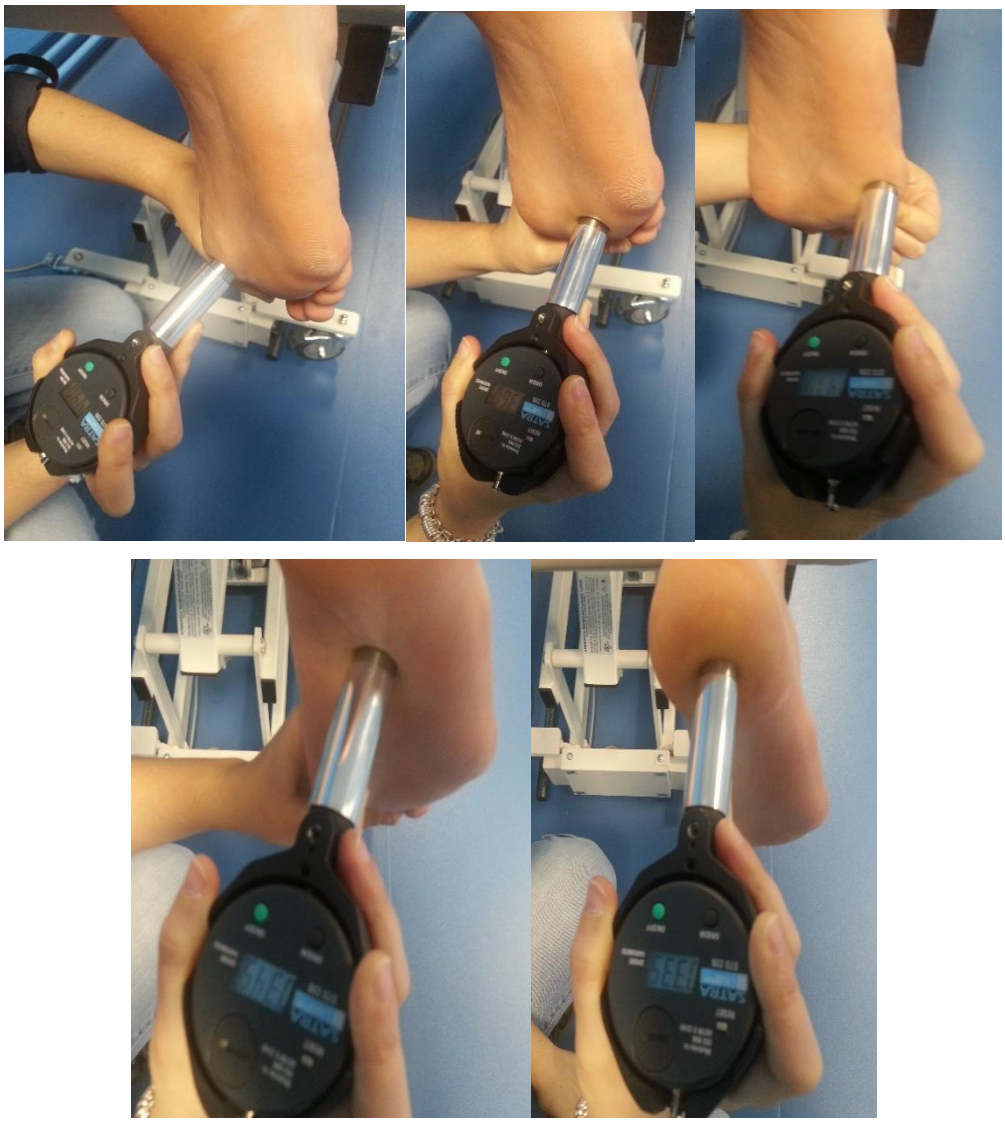

Figure 8.1: Different regions tested with the durometer.

8.4.1.2 Lower limb 3D motion capture

Previous studies have shown that biomechanical variables, such as ankle and 1st MPJ ROM or velocity, influence PP (Fernando *et al.*, 2013). Moreover, foot orthoses are prescribed to reduce PP by modifying foot position and motion during gait. Therefore, it is conceivable that gait pattern and foot motion might have some influence on an individual's response to the insole design. Accordingly, 3D motion data was collected in order to investigate their effect:

Ankle joint maximum angular velocity: the decrease on ankle joint ROM present in patients with diabetes and neuropathy leads to an abnormal joint motion

(Fernando *et al.*, 2013). This lack of mobility on the ankle can also result in an elevated time-dependent load of the forefoot (Fernando *et al.*, 1991), a variable which has previously been found to be one of the predictors of plantar pressure (Payne *et al.*, 2001). Moreover, Rao *et al.* (2010) found decreased ankle moment and power which was associated with increased plantar loading in patients with diabetes.

1st MTJ joint maximum angular velocity time: research has shown that there is a reduction in mobility at the 1st MPJ joint in patients with diabetes and neuropathy (Fernando *et al.*, 2013). The ROM in this joint and its motion during gait has been previously associated with PP (Turner *et al.*, 2007, Barn *et al.*, 2015). Given the consequences that prolonged PP may have in neuropathic tissues, it is important to further understand the influence of this variable in PP.

In order to collect foot motion data, Vicon TM (Oxford, UK) infra-red cameras and passive reflective markers were used. The software package used for the data collection was Vicon Nexus, Vicon's exclusive software. Once the data was collected, it was pre-processed with a custom Matlab program detailed below.

Camera setup and calibration

Motion data collection was performed in the Human Performance Laboratory at Brian Blatchford building where 10 Vicon MTX40-s cameras are fixed on the ceiling (Figure 8.2). Before data collection, both static and dynamic calibrations were performed to extrapolate 3D coordinates from each 2D camera (Richards, 2008). For the static calibration and origin definition, a "T" shaped wand was placed onto the edges of the force plate (Figure 8.3). Also, a dynamic calibration was performed by moving the wand through the volume in which the cameras will record.

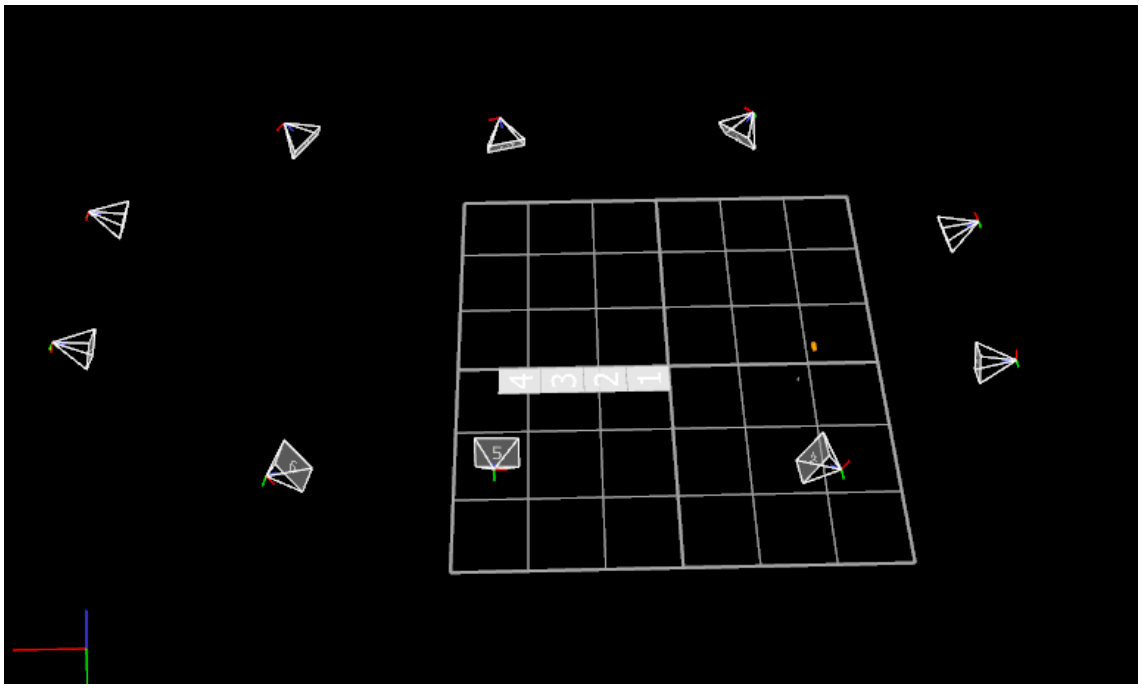

Figure 8.2: Vicon cameras and force plates layout

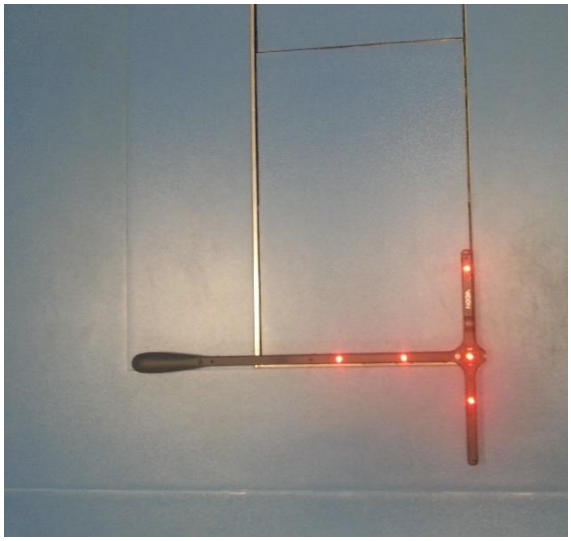

Figure 8.3: Calibration wand on the coordinate origin.

Kinetic data

The ground reaction force was also collected with two fixed Kistler 9281B force platforms. These force platforms were aligned (Figure 8.3) and embedded in the gait lab ground to ensure a consisted height surface allowing the subject to walk normally. Participants were asked to walk over the force plates but were not instructed to hit them while walking. This was achieved by establishing a fixed walking starting point that

allowed them to take a few steps before making contact with the force plates, as well as assuring a consistent speed. The same self-selected speed used for the plantar pressure collection was used for this test. A total of 10 good trials were collected per subject. A trial was considered as good when the subject hit the platform with the leg where the markers were placed (see next section) within the correct speed range.

Kinematic marker set and placement

A multi-segment model for the foot developed in Salford University (Nester *et al.*, 2014) was chosen in order to track the foot movement accurately. To this end, plates with sets of three non-collinear markers were located on each one of the foot segments (Figure 8.4). Also, static markers on the malleoli and internal and external epicondyles were used for the anatomical calibration. Marker sets with a diameter of 9 mm were attached to subject's skin with double-sided tape. Motion data was collected on the leg most affected by neuropathy or the one with the highest PP in cases of bilateral neuropathy (Figure 8.4).

Calcaneus segment was tracked by three markers. Two of them were vertically aligned on the posterior side of the calcaneus, one on the most proximal part of the bone, and the other one just above the plantar fat pad. The third marker was located on the lateral side of the calcaneus just above the plantar fat pad (Figure 8.4).

The midfoot segment was tracked by an elongated plate with three markers attached to it. It was placed on the anterior side of the ankle, with the medial marker on the navicular tuberosity and the lateral marker towards the lateral malleoli (Figure 8.4).

Medial forefoot segment was tracked with a triangular plate with three markers attached to it. It was placed with its straight side along the proximal part of the first metatarsal shaft towards the navicular (Figure 8.4).

Lateral forefoot segment was tracked with a three marker plate located on top of the cuboid and running distally along the proximal part of the fifth metatarsal shaft (Figure 8.4).

Hallux segment was tracked by a plate attached to the top of the hallux with three markers attached to the plate with pins (Figure 8.4). This plate was fixed with tape to the distal phalange of the hallux and was used to define and track this segment.

In addition to the multi-segment foot model, a segment for the shank was defined in order to help calculate ankle mobility. It was defined by static anatomical markers, and its movement was tracked with a plate of four markers.

Shank segment was defined by four static markers, two on the malleoli and two on the internal and external epicondyles. The movement of this segment was tracked using a plate with four markers attached to it; that was placed on the distal third of the leg (Figure 8.4).

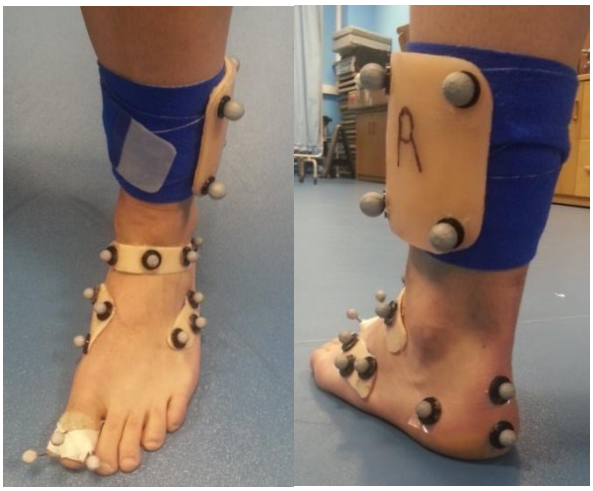

Figure 8.4: Location of the different reflective markers used to define and track foot and ankle movement

Motion data collection protocol

Prior to the data collection, participants were instructed to wear shorts and to take their shoes and socks off. Reflective markers (see the previous section) were attached to their skin using double sided tape on the anatomical regions defined previously, which were located by palpation. Before motion collection, a static calibration was performed, after which the subject was asked to walk over the force platforms at the same self-selected speed used for the plantar pressure (Chapter 5). A total of 10 good trials were collected per participant. For all trials, kinematic data was collected with the Vicon system at a rate of 100 Hz and force data at a rate of 1000 Hz.

8.4.2 Second visit

Only in-shoe pressure data was collected on the second visit. Subjects were asked to walk with each one of the insole conditions that were designed for them. The data collection protocol is detailed in Chapter 5. The pressure data used in this study is the same used in the previous study (Chapter 7).

8.5 Data analysis

Each of the demographic and clinical variables outlined in Section 1.4 were summarised in an Excel sheet. BMI was calculated from height and weight, age from date of birth and tissue stiffness was averaged from the four different recordings taken. All variables collected are presented below (Table 8.1) with the associated ranges of measurement across all participants.

Input feature	Approximate Range of values
Subject demographics	
BMI	21 – 45g/m2
Foot Morphology	Mm
Arch height	25-40
Joint mobility	Degrees
Inversion	15-25
Eversion	5-15
Ankle dorsiflexion	80-110
1st MPJ	5-25
Skin stiffness	Hardness º shore A
1st metatarsal head stiffness	450-600
3rd metatarsal head stiffness	450-600
5th metatarsal head stiffness	450-600
Arch stiffness	250-400
Heel stiffness	350-450

Table 8.1: Variables collected during the 1st visit

8.5.1 Motion data analysis

Once all data was collected, individual markers for each trial were labelled using Nexus Vicon® software, after which the raw marker data was exported to C3D format. This C3D data for each trial was then imported into the Visual 3D software which was used to perform the kinematic calculations. Firstly, a gap-filling algorithm was used to complete marker trajectories in which there was missing data for a maximum of ten frames. A 4th order Butterworth low-pass filter with a cut-off frequency of 12 Hz was then applied to remove noise. Low-pass filters eliminate the high-frequency component of the signal, removing the small random digitising and soft tissue errors. However, it should be noted that the filtering does not change the movement data itself (Richards, 2008). A low pass Butterworth filter was also used to filter the ground reaction force and free moment signals at 25 Hz. A footstep was defined from heel contact to toe-off and was determined using a threshold of 20 N.

8.5.1.1 Kinematic model

The static trial was used to define local coordinate systems for each segment. However, rather than define anatomically based coordinate systems for each of the individual foot segments, the coordinate system, used to define the shank (see segment descriptions above) was also used to define each foot segment coordinate system. Within these local coordinate systems, x was defined to be in the mediolateral direction, y in the anterior-posterior direction and z in the vertical direction. Segmental angular positions (joint angles) and joint velocities were then calculated relative to the laboratory system and also relative to adjacent segments using the Visual 3D software. For these joint angles, x defined the flexion-extension axis, y the abduction-adduction axis, and z the longitudinal axis. Although this kinematic analysis leads to a relatively large number of kinematic trajectories, only a small number were chosen to be included in the subsequent analysis. These variables were selected based on the hypotheses (outlined in section 1.4.1.2; Table 8.2) about kinematic variables and the way in which they may affect the plantar pressure response to insole design.

Variable	Definition	Unit
1st MTP joint maximum angular velocity (x, y, z)	The maximum angular velocity during stance for the 1st MTP joint.	Radians
Ankle joint maximum angular velocity (x, y, z)	The maximum angular velocity during stance for the ankle joint.	Radians

Table 8.2: Kinematic parameters used as algorithm inputs

8.6 Statistical analysis

What factors influence an individual's response to insole design?

Stepwise logistic regression was used to understand the influence of the different clinical/biomechanical variables on the individual subject responses to different insole designs. Logistic regression is a statistical method that investigates the association between a dependent variable (i.e., PP change) and one or more independent variables (i.e., subject's characteristics). With this approach, it is possible to understand the predictive ability of each of the independent variables on the dependent variable. With this technique, the independent variable that has the strongest association with the dependent variable is first included in the model. Then, the independent variable with the next strongest association is included and this process continues until no enhancement of the prediction is achieved.

To perform a logistic regression, the dependent variable has to be categorical whereas the independent variables can be either categorical or scalar. For this analysis, the dependent variable was defined as "PP change" and was quantified, for each insole design separately, by deducting the PP for that insole from the PP recorded from the control shoe. This PP change was then converted to a categorical variable based on the level of variability observed in the repeatability study (Chapter 6) and is detailed in the following section. The subject's characteristics were set as the independent variables. For each one of the subject's characteristics, extreme groups were identified. The idea behind this approach was that the subjects with the extreme values (highest and lowest) for each variable would have the largest changes in PP. A detailed explanation of how these calculations were made is presented below.

8.6.1 Dependent variable calculation: PP change

The effect of the insole was calculated by deducting the PP obtained with each one of the insole conditions from the PP recorded with the control insole. The results obtained from this approach were positive when the insole condition had successfully decreased PP and negative in the cases that PP increased, such as hallux. These changed PP measures were then recoded based on thresholds of 55 KPa (for the metatarsal heads) and 80 KPa for the hallux, thresholds chosen based on the results obtained on the variability of plantar pressure collection in Chapter 5.

Two separate logistic regression models were performed, one investigating the characteristics that influence a reduction in PP and a second investigating the characteristics that influenced an increase in PP. For the first analysis (investigating PP reduction), an insole was classified as effective at decreasing PP if the change in PP was larger than 55 KPa (or 80 KPa for the hallux region), otherwise, it was classified as non-effective (Figure 8.5). For the second analysis (investigating PP increase), an insole was classified as effective at increasing PP if the change in PP was lower than -55 KPa (or -80 KPa for the hallux region), otherwise, it was classified as non-effective (Figure 8.5).

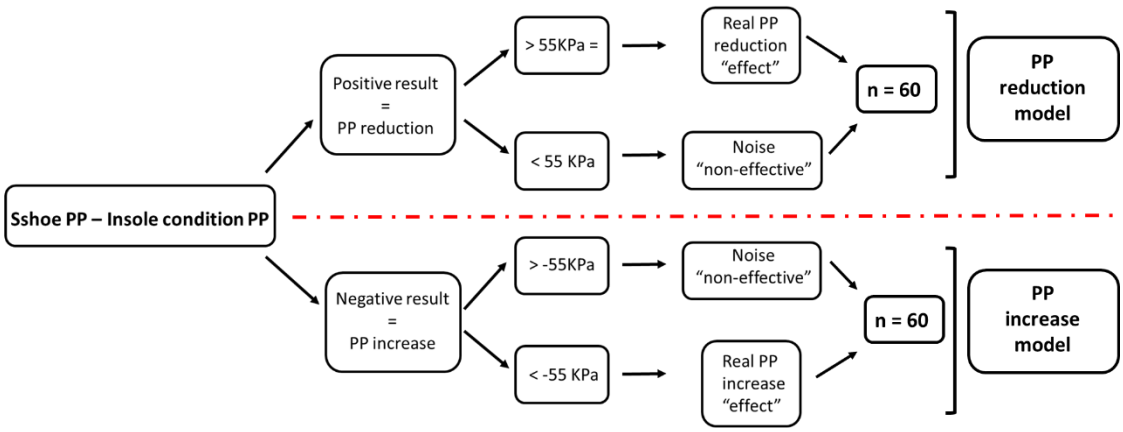

Figure 8.5: Variable recode process for the effect on PP used in each of the logistic regression models

8.6.2 Independent variable calculation: extreme groups of subject's characteristics

The main aim of this study was to find associations between clear differences in the subject's clinical/biomechanical variables (Section 1.4) with unequivocal differences in PP. Extreme groups were defined in order to define clear differences in each of the different clinical/biomechanical variables. Specifically, each variable was recoded into three categories, low, normal and high, based on the distribution of that variable (Figure 8.6). To select the subjects that would go into each one of the categories, quartiles were calculated for each variable. With this approach, the group labelled as "low" included the subjects with values from the first quartile and the group labelled as "high" included the subjects from the upper quartile, with the remaining 50% of subjects in the "normal" group.

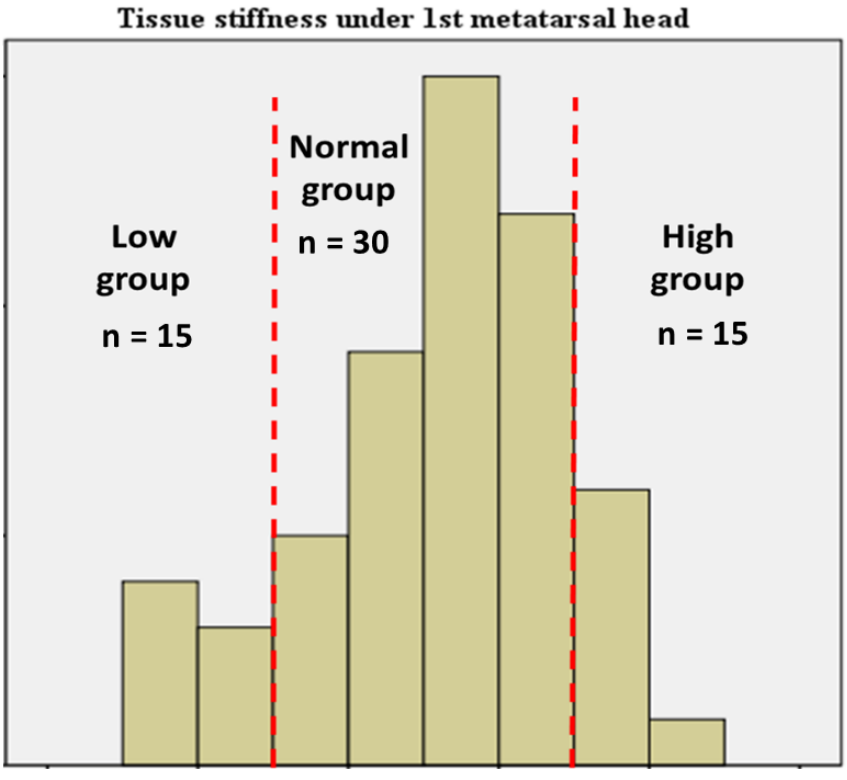

Figure 8.6: Extreme groups for tissue stiffness under the 1st metatarsal head

8.6.3 Logistic regression calculation

Logistic regression analysis is used to explore the relationship and influence that one or several independent variables (subject's characteristics) have on a dependent

variable (change in PP). If two or more independent variables are studied, as was the case in this study, logistic regression can identify the combination of variables to predict the dependent variable. Furthermore, this analysis can be used to identify the independent variable which has the strongest influence on the dependent variable. There are different ways to find this combination, but for this study, the stepwise approach was used, where the independent variable with the strongest association is first introduced into the prediction equation. The next best predictor variable is then entered, and so on until a point is reached when no further enhancement of the model is achieved.

In order to perform the logistic regression and associate specific variables with either a decrease or an increase in PP, it was necessary to hypothesise the potential effect of each variable on the PP change (see Table 8.3).

Variable	Hypotheses for PP reduction
BMI	Low
Arch height	Low
Tissue stiffness	Low
Ankle joint mobility	High
1st MPJ mobility	High
Eversion	High
Inversion	High
1st MPJ joint maximum angular velocity	High
Ankle joint maximum angular velocity	High

Table 8.3: Hypothesis of which category will lead to PP reduction in the logistic regression model for each variable

8.6.4 Logistic regression outcome variables

The logistic regression results are represented by the odds ratio (OR) with its 95% confidence interval (95% CI), the p-value and the Nagelkerke square (r^2). The OR represents the probability that the dependent variable (PP change) will occur given a particular category of the independent variable (high tissue stiffness) compared to the

odds of occurring in the baseline category (low tissue stiffness). In other words, it reflects the odds that PP will change in the presence of high tissue stiffness when compared to low tissue stiffness. The OR values ranged from 0 to infinite, where OR = 1 means that the independent variable has no influence on the dependent variable; OR < 1 implies that the independent variable is considered as a protective factor and for a value of OR > 1 the variable is considered as a risk factor. For example, an OR = 3 for skin stiffness would show that an individual with high skin stiffness would be three times more likely to exhibit high PP compared to individuals with low skin stiffness.

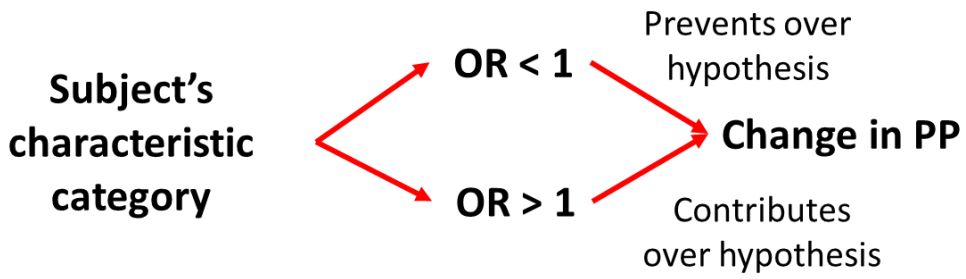

Figure 8.7: OR interpretation. A change in PP would represent either an increase or decrease depending on the logistic regression model

The 95% confidence interval (95% CI) was used to estimate the precision of the OR, with a large CI indicating a low level of precision of the OR, whereas a small CI indicates a higher precision of the OR. It was represented by the minimum and maximum of the OR with 95% confidence.

The p-value represents the statistical significance associated with each regression coefficient within the model. It expresses the probability of OR ≠ 1 representing either a risk or a protection factor.

The r^2 is a measure of the proportion of variation in the dependent variable that can be attributed to the independent variables. It is a measure of the strength of the linear relationship between the dependent and the independent variables; the larger the value of r, the greater the linear relationship.

This study sought to address the following research questions:

1. Which characteristics influence in-shoe PP reduction?
2. Which characteristics influence in-shoe PP increase?
3. Which characteristics could be used to inform the choice of insole design?

To address the first two research questions, two separate logistic regression analyses were performed using the SPSS software for each individual condition and anatomical region. The first analysis was designed to explore factors which influence PP reduction (RQ 1) and the second, to explore factors which influence PP increase (RQ 2). To address the third research question, the results of the first two analyses were compared between the different insoles conditions to identify the characteristics that had an effect on PP and were common across insole conditions. Characteristics that also had an effect on PP but which were not common across insole conditions were also identified and, together, these findings were used to identify characteristics which could be used to inform insole prescription. For example, under the first metatarsal head, the characteristic high tissue stiffness featured in all significant regression analyses being associated with a PP reduction in four insole designs (base/distal metatarsal bars with both poron/EVA). However, low inversion ROM was only associated with PP reduction in one of the four significant regression analyses, base metatarsal bar condition and poron. Therefore, for patients with high tissue stiffness and low range of inversion, base metatarsal bar combined with poron would be appropriate for a PP reduction. However, for patients with a high range of inversion, poron as a cushioning material should be avoided.

8.7 Results

8.7.1 Which characteristics influence in-shoe PP reduction?

8.7.1.1 First metatarsal head

Associations between subject's characteristics and PP reduction were found on four of the nine insole conditions. No associations were found for proximal metatarsal bar position with poron or EVA, or for any of the metatarsal bar positions with a void. High tissue stiffness under the 1st metatarsal head was associated with the prevention of a PP reduction on four different insole conditions (Table 8.4). This shows that individuals with higher levels of tissue stiffness experienced a greater risk of higher PP under this anatomical region than those with low tissue stiffness in the four insole designs identified below. Moreover, a low range of inversion was three times more likely to lead to a lower PP with a poron base metatarsal bar. Finally, for the distal metatarsal bar combined with poron, a low 1st MPJ mobility was twice as likely to achieve PP reduction.

Material condition	Met bar position	Subject's variable	OR	95% CI	p-value	r^2
EVA	Base	1st tissue stiffness	0.290	0.099 - 0.851	0.024	0.147
	Distal	1st tissue stiffness	0.290	0.099 - 0.851	0.024	0.147
Poron	Base	Inversion	3.090	1.038 - 9.202	0.043	0.279
		1st tissue stiffness	0.212	0.067 - 0.673	0.08	
	Distal	1st MPJ ROM	2.574	1.013 - 6.542	0.047	0.224
		1st tissue stiffness	0.266	0.085 - 0.830	0.023	

Table 8.4: Binary linear logistic regression results for predictors of reductions in PP under the 1st metatarsal head.

8.7.1.2 Central metatarsal heads

Inversion was the best predictor of PP reduction with most insole designs (7 out of 9). No associations between subject's characteristics and PP reduction were found for a distal metatarsal bar with both EVA and void. Contrary to our hypothesis, for most conditions, a low inversion ROM was associated with a PP reduction in most significant analyses (Table 8.5). Interestingly, for the base metatarsal bar combined with void, the opposite result was obtained for the inversion. However, although low ankle joint velocity was included in the model, it had a $p > 0.05$, which makes the association not reliable enough.

Material condition	Met bar position	Subject's variable	OR	95% CI	p-value	r^2
EVA	Proximal	Inversion	3.761	1.342 - 10.353	0.012	0.143
	Base	Inversion	3.761	1.342 - 10.353	0.012	0.171
Poron	Proximal	Inversion	3.761	1.342 - 10.535	0.012	0.171
	Base	Inversion	3.244	1.245 - 8.449	0.016	0.148
	Distal	Inversion	4.025	1.390 - 11.654	0.010	0.182
Void	Proximal	Inversion	8.191	2.212 - 30.328	0.002	0.311
	Base	Ankle joint vel	3.514	0.931 - 13.266	0.64	0.377
		Inversion	0.931	1.981 - 42.853	0.005	

Table 8.5: Logistic regression results for predictors of PP reductions under central metatarsal heads

No significant associations were found between a PP reduction and the subject's characteristics for the 5th metatarsal head or the hallux. This may be explained by the results obtained in Chapter 7, where it was found that on average, PP on the hallux increased and under the 5th metatarsal heads, PP stayed approximately the same with all the insole conditions tested.

8.7.2 Which characteristics influence in-shoe PP increase?

8.7.2.1 First metatarsal head

Associations between characteristics and PP increase were only found in two insole conditions. For the distal metatarsal bar position with EVA, a low range of inversion prevented the PP increase. This finding is consistent with the results for PP reduction under the central metatarsal heads (Table 8.6), which showed that PP reduction was 3 times more likely with a low range of inversion. Furthermore, for the proximal metatarsal bar position with poron, the low range of eversion, the opposite subtalar joint movement, prevented increases in PP. Finally, although low 1st MPJ range of movement was identified by the regression analysis, the p-value was greater than 0.05 and therefore the association may not be meaningful.

Material condition	Met bar position	Subject's variable	OR	95% CI	p-value	r^2
EVA	Distal	Inversion	0.173	0.030 - 0.981	0.047	0.179
Poron	Proximal	1st MPJ	6.478	0.771 - 54.436	0.085	0.381
		Eversion	0.034	0.002 - 0.698	0.028	

Table 8.6: Binary linear logistic regression results for predictors of increase in PP under 1st metatarsal head

8.7.2.2 Central metatarsal heads

Significant associations between the characteristics and increases in PP were only found for the distal metatarsal bar with all three material conditions and for the proximal metatarsal bar with poron. For the distal metatarsal bar position with EVA, higher skin stiffness under both heel and the 1st metatarsal head was associated with a prevention of the increased PP. However, although tissue stiffness under the 1st metatarsal head was included in the model, the $p > 0.05$ and therefore, is not significant. Nonetheless, high tissue stiffness under the 1st metatarsal head was strongly associated with increased PP (OR > 16). Furthermore, increases in PP were four times more likely with high skin stiffness under the heel with the proximal metatarsal bar combined with a void. Finally,

a low range of eversion prevented a PP increase with a distal metatarsal bar combined with both poron and void.

Material condition	Met bar position	Subject's variable	OR	95% CI	p-value	r^2
EVA	Distal	1st durometer	0.133	0.014 - 1.258	0.078	0.362
		Heel durometer	16.693	1.648 - 169.081	0.017	
Poron	Distal	Eversion	0.272	0.075 - 0.987	0.048	0.135
Void	Proximal	Heel durometer	4.048	1.085 - 15.105	0.037	0.150
	Distal	Eversion	0.322	0.112 - 0.931	0.037	0.126

Table 8.7: Logistic regression results for predictors of PP increase under central metatarsal heads

8.7.2.3 Fifth metatarsal head

An association between characteristics and PP increase was only found for the distal metatarsal bar with poron. For this condition, high tissue stiffness under the 1st metatarsal head prevented the PP increase.

Material condition	Metbar position	Subject's variable	OR	95% CI	p-value	r^2
Poron	Distal	1st durometer	0.106	0.011 - 0.982	0.048	0.240

Table 8.8: Logistic regression results for predictors of PP increase under the 5th metatarsal head

8.7.2.4 Hallux

Eversion was the variable that influenced PP most frequently under the hallux. Significant associations were found for four separate conditions (proximal/distal metatarsal bar combined with EVA). A low range of eversion movement prevented the PP increase in all cases. In addition to eversion, the PP increase was four times more likely when the ankle joint velocity was low in the proximal metatarsal bar and void condition. Moreover, the high tissue stiffness under the 1st metatarsal head of the distal metatarsal bar with void prevented an increase in PP.

Material condition	Met bar position	Subject's variable	OR	95% CI	p-value	r^2
EVA	Proximal	Eversion	0.168	0.040 - 0.706	0.015	0.220
	Base	Eversion	0.155	0.029 - 0.823	0.029	0.211
Void	Proximal	Ankle joint vel	4.369	1.068 - 20.139	0.041	0.278
		Eversion	0.201	0.055 - 0.733	0.015	
Void	Distal	1st durometer	0.198	0.047 - 0.841	0.028	0.185

Table 8.9: Logistic regression results for predictors of the PP increase under the hallux

8.7.3 Which characteristics could be used to inform the choice of insole design?

At the first metatarsal head, high tissue stiffness was associated with a PP reduction for the base and distal metatarsal bars with both poron and EVA (Table 8.6). Given that high skin stiffness appeared to predict reductions in PP across all four conditions, the presence of high skin stiffness would support the use of a base or distal metatarsal bar with either EVA or poron. In addition, low inversion ROM was associated with PP reduction, but only with the base metatarsal head and poron (Table 8.6), therefore, for patients with high tissue stiffness and low inversion ROM, base metatarsal bar with poron may be the best choice to achieve a PP reduction. However, for patients

with a high range of inversion, poron as a cushioning material should be avoided. Furthermore, under the first metatarsal head, a low 1st MPJ ROM was found to be associated with a PP reduction with poron (Table 8.6), therefore, individuals with lower joint mobility may benefit from insoles incorporating poron, while it should be avoided in patients with higher 1st MPJ ROM.

Under the central metatarsal heads, low eversion ROM was associated with a PP increase with the distal metatarsal bar position with both poron and void material conditions (Table 8.7), indicating that a distal metatarsal bar position should be avoided in patients with low eversion ROM.

Under the first metatarsal, high tissue stiffness under the first metatarsal head prevented PP reduction but only for the distal metatarsal bar position. Interestingly, in the other forefoot regions, high tissue stiffness prevented a PP increase. Consequently, the distal metatarsal bar position may be the most appropriate design to prevent a PP increase in all regions apart from the first metatarsal head for patients with high tissue stiffness under the first metatarsal head.

8.8 Discussion

This study aimed to identify the factors influencing PP change (either increase or reduction), and from these to further understand which subject characteristics may be used to select an appropriate insole design. Logistic regression analyses were performed individually for each insole condition to understand the relationship between the subject characteristics and PP increase/decrease. These results were then compared between the different insoles conditions to identify the characteristics which may be used as a guide for insole prescription.

The results revealed an association between PP change and the following characteristics: high 1st metatarsal head tissue stiffness, subtalar joint mobility MPJ ROM and ankle joint velocity (Table 8.10). Based on these findings and how they differed across different insole conditions, some prescription guidelines have been proposed, see section 8.7.3.

High 1st metatarsal head tissue stiffness	Prevents PP reduction under the 1st metatarsal head
	Prevents a PP increase under the rest of the anatomical regions studied
Subtalar joint ROM	Low inversion contributes to a PP reduction under the central metatarsal heads
	Low eversion prevents a PP increase under all regions studied except 5th metatarsal head
Low 1st MPJ ROM	Contributes to PP reduction under the 1st metatarsal head with distal metatarsal bar
	Contributes to PP increase under 1st metatarsal head with proximal metatarsal bar
Low ankle joint velocity	Contributes to PP reduction under central metatarsal heads
	Contributes to PP increase under the hallux

Table 8.10: Main results for characteristics that influence PP change

This was the first study to investigate the relationship between the subject's characteristics and PP change with an insole design. In contrast, all previous studies have aimed to predict PP, rather than PP changes. Despite this difference in methodology, it is still important to compare the findings of this study with those of previous research in this area. Following this comparison, the possible implications of these results in clinical practice are discussed.

8.8.1 Structural subject's characteristics that influence PP change

1st metatarsal head tissue stiffness

High tissue stiffness under the 1st metatarsal head was found to prevent PP reduction under the 1st metatarsal head (Table 8.10). The main function of plantar soft tissue is as a protective layer, to cushion the bony prominences and to prevent high PP. One of the consequences of peripheral neuropathy in patients with diabetes is tissue stiffening in the plantar aspect of their feet. This stiffening makes the tissues less capable of redistributing elevated pressures, which may explain why there is an ability of the

insole to reduce PP under the 1st MPJ when tissue stiffness is high. This effect, observed in this study, was also predicted by the finite element model developed by Gefen (2003), who showed an increased in PP under the first metatarsal head when the severity of diabetic stiffening of the plantar tissue was increased.

In this study, high tissue stiffness under the 1st metatarsal head was shown to prevent a PP increase in the other forefoot regions (Table 8.10), the opposite to the effect under the 1st metatarsal head. This finding is consistent with the data reported by Mueller *et al.* (2003) who quantified foot structure using 3D images constructed from spiral X-ray computed tomography. Structural measures were then related to PP data using regression analysis. Mueller *et al.* (2003) found that tissue stiffness under the 1st metatarsal head region explained some of the variability in plantar pressures observed in individuals under the central metatarsal heads. These results are in agreement with this study with regard to tissue stiffness under the 1st metatarsal head. However, they studied the variability in PP measurements, while the results in this study are based on PP change while wearing different insoles.

8.8.2 Biomechanical characteristics that influence PP change

1st MPJ ROM

A low ROM at the 1st MPJ made the PP reduction twice as likely when compared with high range ROM under the 1st MPJ (Table 8.10). This association is consistent with the idea of the Windlass mechanism of the foot. At the final stages of the step, MPJ dorsiflexion produces a tightening of the plantar fascia and a supination on the foot. This transforms the foot into a rigid lever that contributes to the push-off (Menz&Morris, 2006). Accordingly, a low ROM of the 1st MPJ would fail to tighten the plantar fascia and foot supination, causing this mechanism to fail. Thus, less force would be generated under this joint during the last stages of the step. Bryant *et al.* (1999) collected barefoot pressures on 30 control subjects, 30 subjects with hallux valgus and 30 subjects with hallux limitus. They found significantly lower pressures under the 1st metatarsal head in patients with hallux limitus, a finding which is consistent with our finding of a ROM at the 1st MPJ being linked to more pressure reduction.

In another study, Menz&Morris (2006) investigated plantar pressure in older people, collecting foot posture, ROM, muscle strength, sensation and toe deformity measurements. They found lower levels of PP in subjects with low ROM on the 1st MPJ. Again, this is consistent with the findings of our study. Turner *et al.* (2007) studied the effect of both ankle and 1st MPJ ROM on PP. They compared healthy subjects to people with diabetes both with and without ulceration history, collecting movements of the ankle joint complex and the 1st MPJ together with plantar pressures. Their results demonstrated a correlation between the gait 1st MPJ ROM and forefoot PP, again demonstrating consistency with the findings of our study.

Interestingly, under the central metatarsal heads, a low 1st MPJ ROM was six times more likely to increase PP compared to high ROM (Table 8.10). It is important to note that this was the opposite effect to that observed under the 1st MPJ itself. It has been suggested that the inability of the 1st MPJ to plantarflex during the propulsive phase of gait leads to increased pressure under the hallux and also, a transfer of load to the other areas of the forefoot (Bryant *et al.*, 1999). Our results are consistent with this concept proposed by Bryant *et al.* (1999) from data showing that subjects with hallux limitus had high PP under hallux, central and 5th metatarsal heads. In further support of this concept, Fernando *et al.* (2013) found that PP increased under the metatarsal heads with increasing 1st MPJ ROM, suggesting that there was an increase in loading times at the metatarsal heads with lower 1st MPJ ROM. However, we did not find any association between this characteristic and the hallux PP. In another study, Payne *et al.* (2001) found that a decrease in the ROM of the 1st MPJ was associated with an increase in PP under the central metatarsal heads. Finally, Allan *et al.* (2015) suggested that this finding could potentially influence insole design or material selection to help reduce the pressure under the metatarsal.

As explained above, there is evidence of an association between a low 1st MPJ ROM and elevated PP in central metatarsal heads (Payne *et al.*, 2001). Furthermore, as these elevated pressures may lead to an increased risk of ulceration, a low 1st MPJ may increase the risk of ulceration. In line with this idea, Zimny *et al.* (2004) compared healthy subjects to both people with diabetes and neuropathy and history of ulceration and people with diabetes but without these risk factors for ulceration. They found a strong correlation between a PTI increase under metatarsal heads and reduced ROM in this joint. They also

reported that pressures were maintained for longer periods of time under at-risk areas, leading them to hypothesise that limited 1st MPJ ROM might be a factor in the pathogenesis of diabetic foot ulcers. In another study, Ledoux *et al.* (2005) investigated the feet of high-risk patients with diabetes, recording forefoot deformities as well as foot type. Interestingly, they found an association between hallux limitus and ulceration under the hallux. Finally, Viswanathan *et al.* (2003) tested four groups: patients with diabetes, patients with diabetes and neuropathy, patients with diabetes, neuropathy and history of ulceration and a healthy control group. Their data showed an increased PP to be associated with 1st MPJ ROM reduction in patients with a history of ulceration, leading them to conclude that both factors could be important determinants of foot ulceration in patients with diabetes. All these studies agree with our results showing that 1st MPJ ROM has a significant effect on PP under the forefoot. Despite the fact that we did not study ulceration risk, high PP has been shown to be one of the main risk factors for ulceration. Accordingly, it can be assumed that when high PP is present, the ulceration risk increases. Interestingly, our results show that distal metatarsal bar helps PP reduction in subjects with low 1st MPJ ROM, which is of key importance for ulcer prevention as shown previously in the studies discussed above.

Subtalar ROM

Inversion and eversion both had an effect on PP reduction for most of the anatomical regions studied. Specifically, a low range of inversion helps to reduce PP under the central metatarsal heads, with a low range of eversion preventing the PP increase under all anatomical regions except the 5th metatarsal head (Table 8.10). This offloading effect can be explained by a precise understanding of the anatomical function of this joint. The subtalar joint is also likely to play a key role in PP absorption and distribution throughout the different stages of the step (Rao *et al.*, 2010). During heel strike, the subtalar joint moves into inversion, facilitating shock absorption and possibly reducing peak force and therefore reducing PP. Then, as the step progresses, it moves towards eversion, which is believed to unlock the forefoot, providing PP redistribution (Rao *et al.*, 2010). It has been suggested that any reduction in the mobility of this joint may cause an increase in plantar pressure during walking (Fernando *et al.*, 1991). Moreover, neuropathy produces a reduction in the ROM of this joint (Delbridge *et al.*, 1988, Rao *et al.*, 2010), with the potential to increase peak pressure.

Based on the theory presented above, a lower range of movement on the subtalar joint should result in an increased PP. However, our results show that the low ROM of the inversion joint contributes to a PP reduction under the forefoot central metatarsal heads. Moreover, our results also showed that a low ROM of this joint eversion prevents the PP increase on all the anatomical regions studied except the 5th metatarsal head. The subtalar joint ROM used in this study were passive measurements rather than gait, but no differences have been found between passive and gait inversion/eversion ROM (Turner *et al.*, 2007). Interestingly, in line with our results, Rao *et al.* (2010) compared dynamic foot function during gait in subjects with diabetes and neuropathy with control subjects. A multi-segment model of the foot was used in this study and barefoot plantar pressures were also collected. Similar to our results, they reported an association between a low range of eversion and PP reduction on the metatarsal heads. Therefore, the theory that reduced calcaneal eversion may result in a less mobile forefoot might not be completely correct and this "unlocking" mechanism might occur in earlier stages of the step. Our results show that both inversion and eversion help to reduce PP under the forefoot while wearing insoles. This reinforces the suggestion made by Rao *et al.* (2010) about the effect that subtalar joint movements have on the forefoot.

Ankle joint velocity

Our results show that the low ankle joint velocity contributed to a PP reduction under the central metatarsal heads and a PP increase on the hallux (Table 8.10). It has been previously shown that a low ankle ROM is associated with an increase in time spent during stance (Martinelli *et al.*, 2013) and this may explain the link between ankle joint velocity and high pressure under the forefoot and hallux. Interestingly, the low ankle joint velocity predicted an increase in PP when present with a low range of eversion. A low range of eversion has been previously shown to help PP reduction under the metatarsal heads (Rao *et al.*, 2010), which also agrees with our results. Accordingly, this PP increase under the hallux might be explained by the redistribution of PP from metatarsal heads (offloaded by a low range of eversion) to adjacent anatomical regions, such as hallux. In another study, Zimny *et al.* (2004) found a strong correlation between ankle ROM and an increase on PTI. Moreover, this PTI increase would result in an elevated time dependent load of the forefoot.

8.8.3 Characteristics that could be used to inform the choice of insole design

To date, there has been very little research investigating the influences of different clinical or biomechanical characteristics on the individual patient response to insole design. Only one study, by van der Leeden *et al.* (2011), has attempted to predict the individual patient's response to different insole prescriptions. However, they based their prediction on the patient's satisfaction and pain reduction rather than quantifiable outcomes, such as plantar pressures. Moreover, they studied patients with rheumatoid arthritis, which are not comparable to the subjects studied in this work, who had diabetes and neuropathy. Therefore, in the discussion above, the focus was on previous studies of factors which have been shown to influence plantar pressure, rather than PP change with an insole design. The key findings of this research and associated explanations are outlined in the following sections.

The main recommendations, outlined in Section 8.7.3, are summarised below:

1. To reduce PP under the 1st metatarsal when high 1st MPJ tissue stiffness is present:
    a. Use a base metatarsal bar with poron if there is low 1st MPJ ROM.
    b. Use a distal metatarsal bar with poron if there is high 1st MPJ ROM.

2. To reduce PP under the central metatarsal heads when both a low range of inversion and low ankle joint velocity are present use a base metatarsal bar with a void.

3. To reduce PP under the hallux, central or 5th metatarsal heads when high 1st metatarsal head tissue stiffness is present use a distal metatarsal bar.

In Chapter 7 (Section 7.5.1.2), the distal metatarsal bar position was shown to significantly reduce PP under the central metatarsal heads. In agreement with those findings, in this current study, a distal metatarsal bar position was shown to help to reduce PP under central metatarsal heads in the presence of high tissue stiffness under the 1st metatarsal head. Interestingly, in this study, the distal metatarsal bar position was also shown to be associated with higher PP under the 1st metatarsal head in the presence of high tissue stiffness under the 1st metatarsal head. This increase in pressure under the 1st metatarsal head with a distal metatarsal bar could be explained by the inability of the stiff tissue to cushion the metatarsal bar closer to the point of PP. Accordingly, for patients

with high tissue stiffness under the first metatarsal head, the distal metatarsal bar position may be an appropriate choice to prevent a PP increase under all the regions apart from the 1st metatarsal head.

In the previous study, poron as the cushioning material was shown to effectively reduce PP under the 1st metatarsal head for all metatarsal bar positions (Chapter 7, Section 7.5.1.1). It was also the material that most frequently lead to lower PP in the previous Chapter (Section 7.5.2). In agreement with those results, in this study poron was shown to contribute to lower PP under the 1st metatarsal head in the presence of high tissue stiffness and low ROM of the 1st MPJ.

Another finding of this study was that the base metatarsal bar contributed to a PP reduction with high 1st MPJ ROM, and distal metatarsal bar in case of low 1st MPJ ROM. The lack of movement on the joint hinders the dorsiflexion that the metatarsal bar may try to produce at the 1st MPJ. Therefore, the closer the metatarsal bar is to the PP, the more effective it may be. These results are consistent with those presented in Chapter 7 that showed that the combination of both base and distal metatarsal bars with poron significantly reduce PP under the 1st metatarsal head when compared to the control shoe (Section 7.5.3.1).

In the previous study, the base metatarsal bar position was shown to lead to lower PP under the central metatarsal heads (Section 7.5.1.2). In line with these findings and based on the results presented in this study, it is possible that the base metatarsal bar position might help to prevent a PP increase under central metatarsal heads in subjects who have a low range of inversion and a low ankle joint velocity. In this case, the base metatarsal bar should be combined with a void as the material condition. However, in the previous chapter, this material condition did not have a significant effect on PP under central metatarsal heads, but it did under the hallux. Moreover, in this study, the results suggest that subjects with a high PP under the hallux should be prescribed a proximal metatarsal bar with void as material condition. Interestingly, this insole design was shown to produce a significant PP reduction under the hallux when compared to the control shoe in the previous study (Section 7.5.3.4).

8.9 Limitations

This study has a number of limitations. The first is that the subjects chosen did not have a history of ulceration and such patients are likely to have a lower PP than subjects with a previous ulcer. Although this population is still at risk of suffering an ulcer, it is conceivable that they may exhibit lower changes in PP with the insole designs tested. Nevertheless, the aim of the study was to investigate the individual responses to customised insoles. To investigate this idea, a threshold-based approach was used to ensure that small (possibly measurement-related) changes in pressure did not influence the analysis. This cautious approach should ensure that only real changes in pressure were related to specific biomechanical and clinical characteristics.

Another important limitation of this study is that a number of the different characteristics were measured using relatively simple tests. It is possible that these tests may not capture the true biomechanical and structural complexity which influences plantar pressure patterns. Nonetheless, most of the variables collected for this study can be easily collected in a typical clinical setting. This means that the findings are therefore more applicable to day-to-day clinical practice.

Self-selected walking speed for each subject was used in this study by calculating an average from five separate preliminary walking trials. All subsequent trials were then accepted if the walking speed was with a ±10% tolerance. Although for many participants, it was possible to work to ±5% tolerance, the participants with diabetes were often not able to repeatedly walk within this tightly controlled speed range. Therefore, speed tolerance was increased to ±10% to ensure participants could complete the testing before becoming fatigued. However, research has shown that walking speed can influence plantar pressures (Segal *et al.*, 2004), so, it is possible that some of the variability in the measurements could be attributed to differences in walking speed between the two days. However, the use of a defined 55 KPa (80 KPa for Hallux) threshold to identify the effect of any insole should have removed the effects of variation in walking speed within the 10% threshold.

9 Summary of the findings

The aim of this PhD was to gain an in-depth understanding of the role of technology in clinical practice and how it can be used improve insole design to reduce PP in medium-risk patients, such as those with diabetes and neuropathy. For this end, four different studies were designed. Firstly, a qualitative study (Study 1, Chapter 4) was performed to understand what practitioners base their clinical decisions on and the role of technology within current practice. Subsequently, three different quantitative studies were developed to gain a better understanding of how technology can be used for insole prescription and for predicting outcomes in medium-risk patients. The first quantitative study (Study 2, Chapter 6) tested the reproducibility of the plantar pressure collection. The second quantitative study (Study 3, Chapter 7) investigated the effect of systematically varying metatarsal bar and material properties on plantar pressure in fully customised CAD-CAM insoles. Finally, the third quantitative study (Study 4, Chapter 8) aimed to identify different subject characteristics that may influence an individual's response to a customised insole design.

9.1 Study 1: An exploration of current practice in relation to engagement with technology

This study had three main aims: to identify 1) what variables practitioners base their prescription design on; 2) what processes are used for assessment and diagnosis of structural foot pathologies and 3) how technology fits within current practice. Focus groups were used to provide an ideal environment for a friendly, open dialogue where different ideas, habits and preferences on diagnosis and prescription were presented and discussed, but not necessarily agreed on. Two sets of focus groups were performed with a total of 17 podiatrists and orthotists with a broad expertise on lower limb pathologies and insole prescription. Different trigger questions were presented to start and throughout the discussion to guide and maintain the dialogue. Focus groups were digitally recorded and transcribed verbatim by a specialist transcription service. The transcripts were then analysed using an iterative approach to thematic analysis as described by (Attride-Stirling, 2001, Darlington, 2002). The results were analysed and presented in two stages:

1) the preliminary themes were identified from field notes only and 2) the preliminary themes were compared with those obtained by all the co-researchers. They were discussed and an agreement was reached providing the final themes, subthemes and a final global theme as an overall conclusion.

The results obtained showed that clinical orthotic practice is mainly based on training and experience and varies between practitioners, reflecting the integration of education with local factors. Decision making for a prescription involves a combination of the patient's needs and expectations, as well as the treatment targets from the practitioner. Interestingly, the influence of research and evidence-based guidelines is limited and not regularly used in diagnosis and prescription. In general, technology is absent from clinical sites and is described as being too complex and time-consuming. However, practitioners agreed that technology would be helpful and appreciated that it has value and could be used to improve clinical practice. One of the most important aspects where technology was identified as being useful was in the measurement of outcomes from practice. Furthermore, a role for technology in developing a prescription and predicting insole effects was a common concern. The possibility of repeatable and accurate prescription and manufacturing provided by the CAD-CAM approach was also appreciated by the practitioners, but it is completely absent from clinical practice. They indicated that for them to invest in new technology, the real added value that it might provide to clinical practice had to be clear. This view shared by all the clinicians during the focus groups, motivated the development of different quantitative studies (Studies 2, 3 and 4) to help to understand the areas where technology can enhance clinical practice.

9.2 Insole design

To investigate how technology can improve insole design, a set of nine different insoles were designed and manufactured using plantar pressure, 3D foot shape and CAD-CAM. First, the 3D foot shape was used to customise the insole top surface using CAD software. The 3D foot shape was combined with the pressure data in order to locate the different defining points of the metatarsal bar and the void. These points were later transferred to the customised insole defining the metatarsal bar and the void distal shapes. Once the metatarsal bar and the void shapes had been designed on the base insole, two more insoles were designed by moving the metatarsal bar proximally and distally. This

process resulted in three different insole designs for each participant. Finally, the insoles were manufactured with a CAM system and two different materials were tailored to fit into the void space. This ultimately allowed the production of nine different insole designs using technology, which were subsequently investigated in the three different quantitative studies.

9.3 Study 2: Reproducibility of plantar pressure collection using a wireless in-shoe pressure device

PP are normally collected in order to assess the ulceration risk in patients with diabetes and neuropathy. For this assessment to be reliable, it has to be both precise and repeatable. However, repeated measurements of physiological/biomechanical variables, such as plantar pressures, are associated with some variability. This variability can arise both from variability in an individual's capacity to repeat a given task, from errors/variability in the measurement processor and from the circumstances under which the measurements take place (de Vet *et al.*, 2006). Reproducibility of in-shoe plantar pressure collection has been studied before by some authors who have demonstrated high agreement and reliability (Ramanathan *et al.*, 2010, Sawacha, 2013, de Castro *et al.*, 2014). However, these studies found good results in healthy subjects while wearing standard shoes with a flat insole (Murphy *et al.*, 2005, Putti *et al.*, 2007, Ramanathan *et al.*, 2010). Consequently, these findings may not extrapolate to patients with diabetes and neuropathy who often use complex customised insoles. This patient group are also likely to have impairments in balance associated with their neuropathy (Allet *et al.*, 2008), which may affect cadence and foot biomechanics leading to inconsistent gait patterns (Allet *et al.*, 2008). Therefore, a clear understanding of the level of reproducibility of plantar pressure measurement in people with diabetes and peripheral neuropathy is needed.

To investigate the reproducibility of plantar pressure collection, pressure data was collected on two separate occasions from eight individuals with diabetes and peripheral neuropathy. On both visits, plantar pressures were collected using a Novel Pedar in-shoe pressure device while wearing standard shoes and different fully customised insoles. For each participant, a total of nine different insole designs were tested (Chapter 5), along

with a standard contoured control insole in a controlled laboratory environment. The data from the two sessions was compared using SEM and ICC to quantify reproducibility.

The results of this study showed that measurements from people with diabetes and neuropathy have a high level of variability. Specifically, SEMs under all metatarsal heads were around 25-30% of the average PP, in the corresponding region. The results for ICC were similar across the different anatomical regions tested, ranging from 0.4 to 0.6, demonstrating moderate to poor reliability. These results illustrate that there can be differences in repeated plantar pressure measurements in subjects with diabetes and neuropathy. It may, therefore, be difficult to differentiate between subjects and to prevent this, in Study 4, we adopted a threshold of 55 KPa (80 KPa for the hallux) above which we were confident of a true change in plantar pressure.

This is the first study to investigate the reproducibility of plantar pressure collection in medium-risk patients while wearing customised insoles. Most previous research in this area has found high levels of reproducibility, however, the research was performed on healthy subjects despite elevated peak pressures being a risk factor for medium or high-risk patients. Importantly, the results of this study showed that measurements of people with diabetes and neuropathy have a high level of variability. This variability may be explained by the abnormal gait that has been reported in patients with diabetes and neuropathy (Fernando *et al.*, 2014). Furthermore, an increase in unsteadiness has been observed in patients with diabetes, most likely due to a more rigid foot less adaptable to walking on different surfaces (Garcia-Alvarez *et al.*, 2013, Allan *et al.*, 2015). Other characteristics of this group include limited joint mobility, limited foot flexibility, a slower gait and a reduced stride (Fernando *et al.*, 1991, Fernando *et al.*, 2013). It is likely that these differences may explain some of the variability observed in our study. However, further research is required to understand the separate influence of each characteristic on plantar pressure variability, and this needs to be factored into future plantar pressure interpretation.

9.4 Study 3: Understanding the effect of systematically varying insole design characteristics on in-shoe plantar pressure

Insoles have shown to be an effective approach for offloading PP in patients with diabetes and neuropathy. However, a total contact insole on its own may not be sufficient to reduce PP in the diabetic foot (Hastings *et al.*, 2007). The most common addition used to reduce PP under the forefoot is a metatarsal bar, which has been shown to be effective under the metatarsal heads (Hsi *et al.*, 2005). However, the precise position of a metatarsal bar can have a considerable influence on pressure reduction under the metatarsal heads (Hayda *et al.*, 1994, Hsi *et al.*, 2005, Kang *et al.*, 2006, Mueller *et al.*, 2006, Hastings *et al.*, 2007, Brodtkorb *et al.*, 2008, Koenraadt *et al.*, 2012). In addition, the use of soft and cushioning materials has also been studied and has shown to be effective for pressure offloading (Healy *et al.*, 2012). In 2007, Paton *et al.* (2007). Of these materials, 6 mm poron offered the best results, and ethyl vinyl acetate was also cited as an effective material (Fernandez *et al.*, 2013).

Cushioning materials and metatarsal bars have both been shown to be effective for plantar pressure reduction. However, there have been no studies investigating the effect of material combined with a customised metatarsal bar position. To address this limitation in previous research and to ensure full reproducibility in designs, a CAD-CAM approach was chosen to design fully customised insoles for each participant based on foot shape and plantar pressure data, combining ay metatarsal bar and cushioning materials. With this approach, we expected to develop a better understanding of the effect of each addition, the interaction between additions, to identify the mean optimum design and to determine the real value of full customization.

A total of sixty subjects with diabetes and neuropathy were tested while wearing the fully customised insoles. The results showed that the combination of a metatarsal bar with cushioning material was an effective approach for reducing PP. In general, cushioning materials led to a significantly lower PP under all metatarsal heads when compared to the void condition. Interestingly, there were no significant differences in PP between the different types of cushioning materials. Regarding the position of the metatarsal bar, both a base and distal metatarsal bar resulted in lower PP under the hallux

and central metatarsal heads. For the rest of the anatomical regions, the metatarsal bar position had no significant effect on PP.

Base and distal metatarsal bar positions most frequently led to significantly lower PP under all anatomical regions. With regard to cushioning materials, poron was shown to achieve the lowest PP under the metatarsal heads most frequently. Taken together, the optimum conditions were the base and distal metatarsal bars combined with poron for metatarsal heads and the same combined with a void for the hallux. These designs also achieved PP reduction for the 1st and central metatarsal heads when compared to the control shoe. Interestingly, a PP increase can be appreciated with all of the insole designs tested on the hallux. Accordingly, we can conclude that the combination of a customised metatarsal bar and cushioning material is an effective approach for reducing PP under the metatarsal heads. These results show that the approach taken in clinical practice of combining metatarsal bars with a cushioning material is an effective approach to reducing PP under the metatarsal heads. However, it should be kept in mind that this design will lead to an increase in pressure under the hallux.

To understand the importance of customization, PP values were compared for each anatomical region, the mean optimal design, the best individual design and the control shoe (Section 7.5.4). Furthermore, the results indicate that the PP distribution with the best subject design remained below 200 KPa for all regions. Moreover, customised insoles managed to reduce the high PP to below 200 KPa in 40% of the subjects. This PP reduction achieved aims to prevent ulceration which, in broader terms, would be highly beneficial not only to the patient but also the NHS, given that each diabetic foot ulcer prevented by a prescribed insole offers a potential cost saving of approximately £23,000 (Paton *et al.*, 2012).

In this study, new technologies were used to design fully customised insoles to reduce PP in medium-risk patients. The customization of the insole top surface was performed using the 3D foot shape, which helped to redistribute PP throughout the plantar aspect of the foot. Moreover, the combination of plantar pressure measurements with a CAD system helped to accurately design and position the metatarsal bar, which has been previously shown to be crucial for PP reduction (Hayda *et al.*, 1994, Weijers *et al.*, 2003, Hastings *et al.*, 2007). The results of this study show that technology can assist in the

design of insoles which are effective in reducing PP. Accordingly, clinical practice could benefit from the accuracy and reproducibility that new technologies can offer to insole design.

9.5 Study 4: Identifying variables which may affect an individual's response to insole design

PP can be influenced by a range of different factors and it is possible that, as well as directly influencing pressure, these factors may also dictate the individual responses to different insole designs. Moreover, insoles are often prescribed to patients with similar characteristics, but insole response is not always positive and it may happen in different time periods for different subjects (Williams *et al.*, 2016). Therefore, a more in-depth understanding is required of the effect of specific clinical, biomechanical and demographic characteristics on individual responses to different insole designs. Such an understanding would lead to effective clinical decision tools which could be used to target orthotic interventions more appropriately.

This study aimed to identify which factors influence PP change (either increase or reduction) and to gain an understanding of which characteristics may affect an individual's response to different insole designs. To address these aims, logistic regression analyses were used to explore the influence of a range of different characteristics on changes in peak plantar pressure. The results of this analysis were then compared across conditions to identify the different characteristics which influence pressure responses in a subset of the different insole conditions. This information was then used to make some tentative clinical recommendations.

Several factors were identified which influenced changes in PP with the different insoles designs. These included high 1st MPJ tissue stiffness which was shown to prevent PP reduction under the 1st metatarsal head, but, in contrast, prevented an increase in PP across the other anatomical regions. Low inversion was shown to be associated with PP reduction under the central metatarsal heads, in contrast with the presence of low eversion, which was shown to prevent PP increase under all regions studied except the 5th metatarsal head. Finally, a low 1st MPJ ROM was shown to contribute to PP reduction

under the 1st metatarsal head, but this effect was only observed with a distal metatarsal bar.

From the associations identified above, it was possible to make some tentative recommendations which may guide prescription of insoles incorporating metatarsal bars and cushioning materials. For example, for patients with high PP under the first metatarsal heads, we recommend a distal metatarsal bar position with poron if both high tissue stiffness and low 1st MPJ ROM are present. Furthermore, a base metatarsal bar with a void should be prescribed to reduce PP under the central metatarsal heads when there is a low range of inversion and low ankle joint velocity.

This is the first study to provide insight into different factors that may influence an individual's response to a specific insole design. The findings demonstrated clear links between both structure and biomechanical characteristics and changes in PP, which occurred with insoles incorporating metatarsal bars and cushioning materials. Although tentative, this allowed us to make some suggestions about insole prescription. These tentative suggestions were made based on customised insoles designed using technology. The results of this work show that technology can help to enhance medium-risk patient's prescriptions and that the individual's response to these prescriptions can be predicted to some extent. Accordingly, the integration of new technologies to help insole design could potentially help to predict treatment outcomes, which would add value to clinical practice.

10 Final conclusions and recommendations

10.1 Recommendations and implications of plantar pressure reproducibility

Our results suggest that reproducibility of PP in patients with diabetes and neuropathy while wearing customised insoles is not high. Interestingly, this finding contrasts with previous literature on healthy individuals which shows lower levels of variability. Clinicians should keep in mind that there is a variability of up to 55 KPa under the metatarsal heads and up to 85 KPa under the hallux on PP measurements in medium-risk subjects. It is possible that smaller changes in PP are the result of variability in walking patterns and this should be factored into future plantar pressure analysis, both in research settings and in the clinic. Although technology is not used very frequently in day-to-day clinical practice, some practitioners who participated in our qualitative study reported using plantar pressure devices to test treatment efficacy in medium-risk patients or in cases where treatment was not successful. Clearly, this type of clinical interpretation of plantar pressure data needs to be performed with caution.

Most of the papers reporting plantar pressure data recruit medium or high-risk subjects such as patients with diabetes or rheumatoid arthritis. However, they collect, analyse and interpret pressure data based on reproducibility results of healthy young subjects who are significantly different to the study population. Importantly, our results have highlighted the differences in reproducibility of plantar pressure data between healthy and pathological groups. Therefore, further research is required to fully understand the factors which affect the reproducibility of plantar pressure collection in medium or high-risk patients. In the meantime, the results of this study should be taken into consideration while interpreting plantar pressure data from research studies which focus on high-risk groups.

10.2 Recommendations regarding insole design

The results showed that both a metatarsal bar and cushioning material are effective at reducing peak plantar pressures under high-risk regions of the foot. This approach has been used in clinical practice for medium and high-risk patients (Williams *et al.*, 2016), but, until now, there was no evidence to support this practice. Our data shows that for patients with high PP under the metatarsal heads, a poron cushioning material combined with a base or distal metatarsal bar is the most effective design. The base metatarsal bar was located just behind the PP and this bar was moved distally 2% of the foot length (the process was detailed in Chapter 5). This finding is of great importance for patients with diabetes and neuropathy who have high PP that predisposes them to ulceration. However, results show that while the PP under the metatarsal heads was reduced, pressures under the hallux were increased. This should be kept in mind by practitioners who prescribe insoles to medium or high-risk patients, given that the hallux can be a common ulceration site.

It was also found that fully customised insoles are beneficial for patients with high PP under the metatarsal heads. PP reduction was obtained under metatarsal heads with all customised designs when compared to the standard shoe alone. Moreover, results from Chapter 7 show that the PP distribution for the best subject insole design achieved values of 200 KPa or lower (Section 7.5.4). This finding is of key importance because 200 KPa was suggested in the literature as a safe threshold for ulceration prevention. Also, the best insole design across subjects achieved PP distributions slightly higher than 200 KPa but still lower that the control shoe. Accordingly, the results show that fully or semi-customization is the best approach to reducing PP close to safe thresholds to prevent ulceration in medium-risk patients.

In the final experimental study, a number of factors were identified which may influence changes in plantar pressure for different insole designs. Although this was an exploratory study, we were able to show that factors which are straightforward to measure in a clinical setting, such as joint mobility, may be useful in guiding future practice for the prescription of insoles with customised metatarsal bars and different material properties. Three main recommendations were suggested based on the insole design subject's characteristics tested in this study:

1. In the case of high tissue stiffness under the 1st metatarsal head, use a distal metatarsal bar to offload central or 5th metatarsal heads and hallux and a base metatarsal bar to offload the 1st metatarsal head.
2. To reduce PP under the 1st metatarsal head in a patient with high tissue stiffness under the 1st metatarsal head, a base metatarsal bar with poron should be prescribed if they have a low 1st MPJ ROM, and distal metatarsal bar with poron if the 1st MPJ ROM is high.
3. To reduce PP under the central metatarsal heads when there is a low range of inversion and low ankle joint velocity, a base metatarsal bar with a void should be prescribed.

10.3 Future research

Study 1 (Chapter 4) was the first study to provide an insight into podiatric clinical practice in the UK and enabled us to understand the different influences on diagnosis and prescription habits. The sample recruited for this study was carefully selected to represent the full range of podiatry clinical practices in the UK and included professionals with a broad range of experience. However, further research is required to fully validate these findings, using larger samples drawn from a wider geographical area, to fully understand what influences clinical practice. Accordingly, national surveys could be performed targeting all practitioners that prescribe insoles to medium or high-risk patients. Another approach would be the creation of online platforms in which practitioners could share diagnosis and prescriptions, as well as review the latest publications or innovations. This type of work would lead to a more uniform consensus of diagnostic and prescription habits which would help to enhance and homogenise podiatry clinical practice across the UK.

Study 2 (Chapter 6) was the first study investigating the reproducibility of plantar pressure collection with an in-shoe device in subjects with diabetes and neuropathy. Unlike all the previously published studies, the results obtained showed a high variability in plantar pressure collection (SEM ≈ 55 KPa). Further research is now required to better understand the factors which may influence the repeatability of plantar pressure data in medium or high-risk patients. These studies should collect PP data from medium or high-

risk patients, such as those with diabetes or rheumatoid arthritis, along with biomechanical data on other factors, such as gait variability, balance and muscle function. Another factor which needs to be investigated is the influence of different time periods between testing sessions. This could be achieved in a study with three or four different visits with longer and shorter time lapses between them, such as the second visit two days after the first test, third visit one week after, and the fourth visit after one month.

Study 3 (Chapter 7) showed that the combined effect of metatarsal bars and cushioning materials are an effective approach for reducing PP. However, the sample recruited for this study had no history of ulceration, and, as a result, appeared to exhibit lower pressures than other similar studies investigating high-risk groups. Therefore, it would be interesting to investigate the effect of both additions in subjects who would be considered a high-risk group and who would demonstrate very high PP. These studies could recruit subjects with foot deformities, such as claw toes or flat feet, which have been associated with both a higher PP and higher risk of ulceration in the literature. Also, subjects with a history of ulceration have a higher PP and represent a very high-risk population. The higher PP that these samples have may facilitate the understanding of the interaction effect of these two additions and the possible enhancing effect on PP reduction.

Study 4 (Chapter 8) was designed to identify characteristics which could be tested in a clinical setting and could inform the decision-making process for insole prescription. As a result of the high variability in the pressure data (Study 2), we defined specific thresholds to identify insole conditions which had a definite effect on peak plantar pressures. However, it is likely that if patients with high pressures at baseline were tested, then larger differences in peak pressures may have been observed. This may have removed the need to impose thresholds and may have given a clearer indication of the different effects of the different insole designs and how these link to individual characteristics. Also, the characteristics used in this study were relatively simple and easy to measure in clinical practice. However, they may not be the most representative characteristics that influence PP. This emphasises the need for more advanced clinical tools to help practitioners measure more complex characteristics that may have an influence in PP, and therefore, in their prescription process.

More complex approaches such as Neural Networks might provide a more thorough understanding of the factors that influence PP behaviour. Another popular approach is FEMs, which are developing fast and becoming more accurate. This approach also has the advantage of offering the possibility of testing many different insole designs without the manufacturing costs and time-consuming testing sessions. Moreover, these research approaches could incorporate factors that are complex and hard to measure in real subjects. They could help narrow the number of variables that influence PP change in individuals, informing future studies on human subjects. The outcomes from these more complex studies might be useful for podiatrists who work in multidisciplinary departments and have access to more complex clinical tests. Moreover, they might provide a better understanding of why similar patients have different responses to the same prescription.

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12 Appendix 1: Qualitative study university ethics approval

Research, Innovation and Academic Engagement Ethical Approval Panel

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24 October 2012

Dear Anita,

RE: ETHICS APPLICATION HSCR12/62 – Current approaches to the prescription of foot orthoses and specialist footwear

Following your responses to the Panel's queries, based on the information you provided, I am pleased to inform you that application HSCR12/62 has now been approved. If there are any changes to the project and/ or its methodology, please inform the Panel as soon as possible.

Yours sincerely,

Rachel Shuttleworth

Rachel Shuttleworth
College Support Officer (R&I)

13 Appendix 2: Participant information sheet for the qualitative study

PARTICIPANT INFORMATION SHEET

What is the purpose of the study?

Foot orthoses is one of the main interventions for foot related pathology. However, there is a lack of knowledge about how current approaches to the prescription in relation to the role of foot geometry and pressure, materials used, and how these factors are combined in a bespoke insole product. Further, it is unclear how practitioners prioritise those factors with greatest impact on the foot health of their patients and for their professional practice and how these factors might integrate with technology. This qualitative study aims to support the development of a set of technological devices and computer tools that will assist practitioners to achieve the best therapeutic orthotic prescription for their patients.

Why have I been chosen?

You have been chosen because you are a practitioner who has experience of prescribing foot orthoses.

Do I have to take part?

Taking part in the research is entirely voluntary. It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep. If you take part you are still free to withdraw at any time and without giving a reason. A decision to withdraw at any time during the study, or a decision not to take part, will not affect any current or future links that you may have with the University of Salford, Directorate of xxxx or the School of xx.

What will happen to me if I agree to take part?

You will be contacted by the researcher whose details appear at the end of this information sheet. Any questions you may have will be answered. You will receive travel reimbursement and any other reasonable expenses. The study will take place between January 2013 and December 2013 at the University of Salford and a specific day and time will be provided to you. As we are using focus groups as the method to collect the data you will be in a group of 8 other practitioners. Each focus group will be facilitated by both Dr. Anita Williams and Dr. Ana Martínez Santos. Before the focus group starts, a presentation will be delivered on recent technological advancements in assessing patients for foot orthoses by Dr. Ana Martínez Santos.

What are the possible disadvantages and risks of taking part?

There are no physical risks associated with taking part in focus group work. It is acknowledged by the researchers that you, as a practitioner will be voicing your opinions and revealing your own thoughts on professional practice. We endeavour to create a respectful environment in which every participant will be supported to voice their opinions. Any unreasonable challenges or comments made by other members of the group will be dealt with sensitively by the facilitators. You are within your rights to withdraw from the process of data collection should you feel uncomfortable or unable to continue and you will be supported in this decision by Dr. Anita Williams and Dr. Ana Martínez Santos. If you do withdraw then you will be able to decide whether or not your contribution is included in transcription of the audio recording and the data analysis.

What are the possible benefits of taking part?

You will receive information about technology which has the potential to enhance the prescription of diabetic foot orthoses. You will also be able, as part of the focus group, to share good practice and also debate the challenges of the prescription process.

Will my taking part in this study be kept confidential?

Confidentiality will be maintained at all times through the study and in the use of data following the end point of the study. All information which is collected during the

study will be locked in a secure filing cabinet and electronic data stored on a password protected computer and server at the University of Salford. Any information about you will have your name and address removed so that you cannot be recognised from it and a code used for tracking you through the study. Only Dr. Anita Williams and Dr. Ana Martínez Santos will have access to your name and address for the purpose of initial contact, contact for the interviews and to post a summary of the results once the study has been completed. Data and personal information will not be provided to any third party.

What will happen to the results of this research study?

Once the research is complete the work will be published in professional journals and presented at conferences. A general acknowledgement for your contribution to the study will be included if you request this. Further, a summary of the results of this study will be sent to you for your own information. All paper records and recorded data will then be destroyed.

Ethical Approval

Ethical approval for this study has been obtained from The University of Salford Research Ethics Committee

Contact for Further Information

Dr. Anita Williams: a.e.williams1@salford.ac.uk

Dr. Ana Martínez Santos: a.martinezsantos@edu.salford.ac.uk

University of Salford
Frederick Road, Salford, M6 6PU
0161 295 7027

Thank you for reading this Information sheet and considering your inclusion in this study

14 Appendix 3: Qualitative study participant consent form

CONSENT FORM

Study Title: Current approaches to the prescription of foot orthoses and specialist footwear

Please initial each box if you agree

1. I confirm that I have read and understand the information sheet dated XX/XX/XX version X) for the above study and have had the opportunity to ask questions. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my current or future links with the University of Salford being affected. ☐

3. I agree to my verbal responses in the focus group being audio taped ☐

4. I understand that a pseudonym will replace my name in the results of this study when published or presented in any form. ☐

5. I request that I am acknowledged by name at the end of publications and presentations ☐

6. I agree to take part in the above study. ☐

Name of Participant _____ Date___/___/___

Signature of Participant_____

Name of Person taking consent (if different from the researcher) _____
Date___/___/___ Signature_____

Researchers name _____ Date___/___/___

Signature_____

1 copy for participant; 1 copy for researcher

15 Appendix 4: Quantitative studies NHS ethics approval

Stockport NHS
NHS Foundation Trust

Research & Development Office
F08, Pinewood House
Stepping Hill Hospital
Poplar Grove
Stockport
SK2 7JE
Tel: 0161 419 5801 / 5814
E-mail:
research.development@stockport.nhs.uk

Dr Stephen Preece,
School of Health Sciences,
Centre for Health Sciences
Research Office: P.O. 33,
Brian Blatchford Building
Fredierick Road Campus,
University of Salford,
Salford
M6 6PU

04 November 2013

Dear Dr Preece,

Research Office Reference Number: 2013041 Project Title: SMARTPIF Diabetic insole design

REC number: 13/NW/0331

NIHR CSP No: 115521

Thank you for your application for Research Office approval for the above study.

I am pleased to confirm that we have now received and reviewed all necessary documentation, and Stockport NHS Foundation Trust has no objection to being a Participant Identification Centre (PIC) for this study.

Please note, as a PIC, activity at Stockport will be limited to identifying eligible patients and sending out Patient Information Sheets and Patient Invitation Letters.

I would like to take this opportunity to wish you well with your research.

Yours sincerely,

Christine Harvey

Research & Development Manager

cc: Dr Ana Martinez Santos

16 Appendix 5: Quantitative studies university ethics approval

Research, Innovation and Academic Engagement Ethical Approval Panel

College of Health & Social Care
AD 101 Allerton Building
University of Salford
M6 6PU

T +44(0)161 295 7016
r.shuttleworth@salford.ac.uk
www.salford.ac.uk

13 December 2013

Dear Ana,

RE: ETHICS APPLICATION HSCR13/67 – SMARTPIF - Smart tools for the prescription of orthopaedic insoles and footwear

Based on the information you provided, I am pleased to inform you that application HSCR13/67 has now been approved. Please ensure that you include on the participant information sheet that the study has had R&D approval and University Ethics approval.

If there are any changes to the project and/ or its methodology, please inform the Panel as soon as possible.

Yours sincerely,

Rachel Shuttleworth

Rachel Shuttleworth

College Support Officer (R&I)

17 Appendix 6: Quantitative studies participant information sheet

School of Health, Sports and Rehabilitation Sciences

Participant Information Sheet

SMARTPIF – Diabetic insole design

You are being invited to take part in a research study to help us develop a new way to prescribe insoles for people with DM. Before you decide, it is important for you to understand why the research is being done and what it will involve. This document gives you important information about the purpose, risks, and benefits of participating in the study. Please take time to read the following information carefully. If you have any questions then feel free to contact the researcher whose details are given at the end of the document. Take time to decide whether or not you wish to take part.

BACKGROUND TO THE STUDY

People with DM are at risk of developing foot ulcers. To reduce this risk, special insoles are often prescribed to reduce pressure under the foot. These insoles are designed so that the pressures are not high under the foot, due a specific device and/or with a cushioning material. Although these insoles are used widely by diabetic patients, we do not know the best design for each individual. This research project will test how different design features change the pressure under the foot and develop a quick and simple way to choose the best insole design for each person.

The study will involve 60 participants with DM. Participating in this study is completely voluntary and you may withdraw at any time. A decision to withdraw at any time, or a decision not to take part, will not affect the care you receive.

WHAT WILL HAPPEN TO ME IF I PARTICIPATE IN THIS STUDY?

How long will it take?

If you agree to take part in the study, you will be required to visit the movement science laboratory at Salford University on two or three occasions. The total time for each visit is 2-3 hours.

The first visit will involve:

- Taking consent (10 minutes)
- Clinical tests on your feet (neuropathy, joints and skin tests) (10-15 min)
- Scan of the shape of your foot (5 minutes)
- Walk over a pressure measurement plate 10 or 20 times (15 mins)
- Have reflective markers attached to your legs and feed and walk over a force plate whilst we record your way of walking (30 mins)
- Walking up and down the assessment room in a specific pair of shoes whilst we measure pressure under your foot (10 minutes).

The second visit will involve:

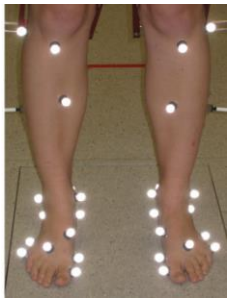
- Walking up and down the assessment room 4 or 5 times in 10 different pairs of insoles (60 minutes)
- You will then be offered to chance to keep and use a new pair of insoles (one of the set you have used during the testing) along with the shoes. It is up to you if you want to keep these insoles and shoes. If you do keep them then you will be required to visit the lab a third time (see details below). Before you take the new insoles/shoes we will ensure that they reduce pressure when compared to your current footwear choice.

The third visit will involve:

- Walking up and down the assessment room in the selected insoles used during the last two weeks (15-20 minutes)
- In case you want to keep the insoles, you will be provided with a prescription which specifies the insole design so you can go to your podiatrist or orthopedist and ask for a new pair.
- Measurement of the fatty pads under your foot (30 minutes)

Further details on the specific tests?

1. **Consent and medical screening:** We will first test your feet and legs for diabetic neuropathy. This will involve touching different parts of your foot with a vibrating tuning fork and then a thin wire and asking you if you can feel anything. The reflexes in your calf muscles will also be tested. Then we will perform some movements on your feet to measure how much do your joints move.
2. **Footscan:** this will involve placing your foot in a box containing a number of special cameras which record data for approximately 5 seconds and then generate a 3D picture of your foot.



3. **Attaching reflective markers:** You will be asked to wear shorts, and we will stick on your skin reflective markers on your hip, legs and foot. When all the markers are placed, you will be asked to walk up and down with them while specific cameras record your walking. These cameras only record the markers movement and send this data to a computer that will join them and make a schematic image of your legs and how they move.
4. **Walking in different pairs of insoles:** We want to assess how different insole designs change the pressure under your foot as you walk. To do this we will use an in-shoe pressure measurement system which has a pressure sensing insole connected by wires to a transmitter worn on your waist, as shown in the picture opposite. You will be asked to walk in each pair of insoles for 3-5 minutes each whilst we record in-shoe pressures with this system.
5. **Measurement of the fatty pads under your foot:** You will be asked to seat and your foot will be positioned using a specific boot to ensure that it remains still during testing and also permitting you to relax the foot. The device will push against the bottom of your foot, loading and then unloading the it in a similar way to walking. During this loading some ultrasound data will be collected to see how your skin behaves while changing pressure. This testing poses no risk to you as the loading is similar to that during normal walking.

Expenses

The researcher team will arrange and pay for a taxi to pick you up and to take you back home at the end of each visit. If you prefer to make your own transport arrangements, we will refund any reasonable travel expenses.

RISKS & POTENTIAL BENEFITS OF THE STUDY

What risks are involved in participating in the study?

This is a very simple, straight forward study with negligible risks. The foot pressure measurements will be operated by an experienced researcher, and involves well-designed technical equipment that has been used for many years both in movement science laboratories and in routine patient care in hospitals around the world.

In case you accept coming a third time and using the insoles we will offer you on the second visit, there is a small risk of blister formation. To avoid this from happening we will give you specific instructions to start using the insoles, and how to identify any risky area.

If I participate in this study, can I also participate in other studies?

As the testing for the SMARTPIF project only takes two or three visits and there is no on-going treatment or assessment taking part should not affect any other studies that you are involved in. However, if you are already taking part in other research, or would like to do so, please discuss this with the researcher (Dr Preece)

What benefits are involved in participating in the study?

You will be given a pair of insoles and footwear that assures a pressure reduction under your feet while walking. You will also be given a ”love2shop” £20 voucher in each visit that you can use in a wide range of stores. Furthermore, the results from your participation on this study, should improve our understanding of how to produce insoles for individuals with DM which reduce their chance of developing an ulcer. In the future this should enable us to quickly design and produce insoles which minimize pressure problems for people with DM; this will ultimately reduce the number of ulcers and complications, such as foot amputation.

What if something goes wrong?

The university has insurance to cover against any harm to you which may occur whilst you are taking part in these tests. However, if you decide to take legal action, you may have to pay for this. If you wish to complain, or have any concerns about any aspect of the way you have been approached or treated during the course of this study, you can approach the University of Salford and if you are not happy you may then go through the standard NHS complaints procedure.

ENDING THE STUDY

What if I want to leave the study early?

You can withdraw from this study at any time without loss of any non-study related benefits to which you would have been entitled before participating in the study. If you want to withdraw you may do so by notifying the study representative listed in the "Contact Information" section below.

FINANCIAL INFORMATION

Who is organizing and funding the research?

The European Union is funding this study which is part of the SMARTPIF project.

Will I be paid for participating?

Although we are not permitted to pay cash we will offer each participant a love2shop £20 voucher, which can be used to buy goods from a wide range of different stores, each time you attend for testing at the University of Salford.

CONFIDENTIALITY OF SUBJECT RECORDS

Will my taking part in this study be kept confidential?

All information which is collected about you during the course of the research will be kept strictly confidential. Any information about you which leaves the University of Salford will have your name and address and any other identifying features removed so that you cannot be recognized from it.

What will happen to the results of the research study?

A summary of the research findings will be sent to everyone who participates in the experiments. Significant findings may be published in clinical and engineering journals.

CONTACT INFORMATION

If you require more information about the study, want to participate, or if you are already participating and want to withdraw, please contact

Dr Ana Martínez
Email: a.martinezsantos@edu.salford.ac.uk
Phone : 0161 295 5311 // 07756112637
Address : School of Health, Sport and Rehabilitation Sciences
Room 34, Blatchford Building, University of Salford,
Frederick Rd Campus,
Salford
M6 6PU

If you have any complaints, please contact

Anish Kurien
R&I Manager
Email: A.kurien@salford.ac.uk
Phone: 01612955276

RECORD OF INFORMATION PROVIDED

Your will receive a copy of the information sheet and a signed consent form to keep for your personal records.

Thank you very much for taking time to read this document!

We appreciate your interest in this study and hope to welcome you at the School of Health, Sport and Rehabilitation Sciences, University of Salford.

18 Appendix 7: Letter of invitation to participants for the quantitative studies

(IN PRACTICE'S HEADED PAPER)

-RESPECTIVE DATE-

Dear --------Patient's name--------,

I am writing to you to offer you the chance to take part in a research study to develop new preventative insoles for patients with DM at the University of Salford. An information sheet with all the details of the study is enclosed. If you would like to take part, or would like further information, please contact Dr Ana Martínez at the University by post, phone or email (details given below) who will arrange a suitable time for you to visit the University. If you choose to participate, the University will cover your travel expenses, any loss of earnings and offer you a £20 gift voucher.

If you do not wish to participate then please ignore this letter.

Yours Faithfully,

--------General Practitioner--------

Contact Details:

Researcher's Name: Dr Ana Martínez
Email: a.martinezsantos@edu.salford.ac.uk
Phone : 0161 295 5311
Address : School of Health Sciences
Room 34 , Blatchford Building,
University of Salford,
Allerton Campus,
Salford
M6 6PU,
Website: http://www.healthcare.salford.ac.uk/

19 Appendix 8: Radio script for quantitative studies recruitment

Contact	E:Sam.Young@Thisisglobal.com		T:0161 6624753	F:01612790354
Global				
Client	University of Salford		Job / Audio ID	
Title	"Insole Research"		Duration	30"
Creative	Sam Young		Airtime	Rachael Browne
Produce By			TX Date	
Station(s)	Capital FM Manchester			

FVO - Bright, Professional.

FVO: **The University of Salford is currently researching how to design Insoles which will be used to treat a range of foot problems. We're looking for volunteers with DM to come to our lab and test our insoles.**

If you're interested in getting involved in our research, and suffer with DM, then we'd like to hear from you.

All volunteers will receive payment for their time and have travel expenses covered.

For more information contact The University of Salford today simply text the word 'insole' to 81156 that's 'insole' to 81156.

20 Appendix 9: Quantitative studies phone screening sheet

Crib sheet for participants recruited through radio advert

Basic information

1. Name:
2. Address:
3. Phone:
4. Shoe size :

Recruitment information

5. DM duration (at least 5 years)?
6. Type DM?
7. Neuropathic? Yes / No
8. Any surgery on the foot? Yes / No
9. Any foot deformity? Yes / No
10. Walking problems, e.g. are you able to walk for 2-3 minute spells several times? Yes / No
11. Any balance problems, walk with cane? Yes / No
12. Feet problems, e.g. current blisters, ulcers? Yes / No

21 Appendix 10: Quantitative studies participant consent form

Center Number:
Study Number:

Patient Identification Number for this trial:

CONSENT FORM

Title of Project:

SMARTPIF – Diabetic insole design

Name of Researcher:

Ana Martínez, PhD, Postgraduate Research Student, School of Health Sciences, University of Salford, Salford, M6 6PU.

Please initial the boxes:

1. I confirm that I have read and understood the **Patient Information Sheet** dated _____ (version 2) for the above study and have had the opportunity to ask questions. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐
3. **I understand that sections of any of my medical notes and data collected during the study will be kept up to 5 years, and may be looked at by individuals from the University of Salford, from regulatory authorities or from the NHS trust, where it is relevant to my taking part in research. I give permission for these individuals to have access to my records.** ☐
4. I agree to take part in the above study. ☐

Name of Patient	Date	Signature
Name of Researcher	Date	Signature

22 Appendix 11: 1st visit data collection sheet for the quantitative studies

Subject nº: **Date of birth:** **Shoe size:**

Weight: **Height:** **Arch height:**

Neuropathy

Monofilament

	1st toe	3rd toe	5th toe	1ºMTF	3ºMTF	5ºMTF	Med Arch	Lat Arch	Heel	Dorsum
Right										
Left										

Tuning fork

	Med malleolus	Lat malleolus	1st met head	5th met head
Right				
Left				

Neuropathy Symptom Score (NSS)

	Unsteadiness in walking	Burning, aching pain or tenderness	Prickling sensation	Numbness
Right				
Left				

Joint mobility

	1st toe	ASA	Inversion	Eversion	TPA knee flx	TPA knee ext
Right						
Left						

Durometer

	1ºMTF		3ºMTF		5ºMTF		Med Arch		Heel	
Right										
Left										

Motion capture

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Speed															

23 Appendix 12: 2nd visit data collection sheet for the quantitative studies

Subject nº

Inshoe pressure (randomized)

	1	2	3	4	5	6	7	8	9	10
Shoe										
Stand										
Cond 1										
Cond 2										
Cond 3										
Cond 4										
Cond 5										
Cond 6										
Cond 7										
Cond 8										
Cond 9										
Cond 10										