INVESTIGATION OF THE PODIATRIC MODEL OF FOOT BIOMECHANICS

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“Love will tear us apart” (Joy Division, 1980)

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Thankyou to my grandmother, who sadly does not get to see the end of this project, her support, love and determination has continued to inspire me.

Abbreviations

ROM: range of motion

DF: dorsiflexion

PF: plantarflexion

INV: inversion

EVER: eversion

ABD: abduction

ADD: adduction

Peak +ve: Peak positive angle (dorsiflexion/inversion/abduction)

Peak –ve: Peak negative angle (plantarflexion/eversion/adduction)

Max: Maximum

Min: Minimum

NCSP: Neutral calcaneal stance position

RCSP: Relaxed calcaneal stance position

MTPJ: Metatarsophalangeal joint

FPI: Foot Posture Index

MEDIAL FF/MedFF: Medial forefoot

LATERAL FF/LatFF: Lateral forefoot

CAST: Calibrated Anatomical Systems Technique

SPSS: Statistical Package Social Science Software

Abstract

Background: Understanding the biomechanical function of the normal human foot is essential so to be able to determine the parameters of what is the abnormal or pathological foot. The current model used in podiatry to describe the normal biomechanical function and assessment of the foot presents many key difficulties. Such as the poor reliability and questionable validity of many of the examinations used in the assessment of the foot and the incorrect assumption that all normal feet will display exactly the same biomechanical function during walking. Although technological advancements in gait analysis have improved our understanding of foot biomechanics this new information has not yet not yet significantly changed clinical practice.

Objectives: The aim of this investigation was a. Derive a consensus on what podiatrists currently use for conducting a static biomechanical assessment of the foot, b. To test the Root et al (1971, 1977) description of the function of the foot during gait cycle and c. To determine if the measurements obtained from a static biomechanical assessment of the foot as described by Root et al (1971, 1977) can predict the movement of the foot during the gait cycle.

Methods: Data was collected from 100 asymptomatic participants and included a static biomechanical assessment of the foot developed from the consensus agreement in part a. and the measurement of the three dimensional kinematic function of the foot during the gait cycle using a six segment foot model.

Results: The results indicate that there is a large variation in the kinematic function of feet during walking and the results of a static biomechanical assessment of the foot cannot predict the dynamic function of the foot.

Conclusions: This suggests that the key principles of the current model used to describe the biomechanical function of the normal foot in podiatry are incorrect and the methods used by podiatrists in clinical practice are not valid.

CHAPTER 1 - INTRODUCTION

1.1 Chapter Overview

The role of the podiatrist is to assess, diagnose, and treat common and complex disease and disorders of the foot and leg. This can include skin, soft tissue, and nail pathologies, or injuries to the musculoskeletal system (Lorimer et al 2002, Farndon et al 2006). There are various specialist areas within podiatry. These commonly focus on diabetes, neurological disorders or arthritic feet, sports injuries, and foot disorders in the children and the elderly. Podiatry has grown in popularity, and significantly increased its profile among research and clinical practice. One of main aims of the Society of Chiropodists and Podiatrists is for podiatry to become synonymous with foot health, and that podiatrists should be the first portal for information about, assessment and treatment of the foot.

Podiatry is commonly taught as a three, or four year undergraduate degree programme with honours in Europe and Australia. In the United Kingdom, there are 13 podiatry schools. Most proceed to work for the NHS, or private practice, but some choose a career in research on completion of their degree course. In the United States of America, podiatrists have undergone medical training first and then choose to specialise in podiatry. Although the remit of their position is quite different, and will commonly involve more surgical based methods.

There are some high profile conferences held worldwide focusing on research, and clinical based methods for treating disease, deformity and disorder of the foot. Most commonly this will include either an individual countries society of podiatry conference. Or organisations such as the international society of foot and ankle biomechanics (iFAB). These have gained much interest from podiatrists, and other allied health professionals who specialise in foot and ankle biomechanics.

Podiatric biomechanics is the specialist area of podiatry, which focuses on the application of mechanical principles to the foot to diagnose, explain, and treat a wide range of lower limb problems. Typically, this will involve the use of a foot orthoses to adjust foot position and movement. Agreeably, podiatric biomechanics have become almost synonymous with orthoses prescription. Podiatrists can propose to offer both the clinical understanding of foot function, but also a good understanding of the mechanical properties of the materials used to construct orthoses.

The current description of the biomechanical function and assessment of the foot is based on the pioneering publications by Merton Root, William Orien, John Weed, and Robert Hughes. They were all podiatrists from the United States of America, and developed these descriptions while working in clinical practice, and as lecturers at the California School of Podiatric Medicine, San Francisco. The first publication was *"Biomechanical examination of the foot"* in 1971. This detailed the protocol for conducting a static based biomechanical assessment of the foot. The second publication was *"Normal and abnormal function of the foot"* in 1977. This described what they perceived to be representative of normal, and abnormal function of the foot during the gait cycle. There was also an additional less well known publication, entitled *"Neutral Position Casting Techniques"* in 1971. This described the casting techniques for the design of the functional foot orthoses.

The Root et al (1971, 1977) descriptions of the normal and abnormal foot remain still today at the forefront of podiatric biomechanics, and the majority of footwear and orthoses design is based on this seminal work. McPoil and Hunt (1995) described how it was the first significant clinical based model of foot biomechanics, and that it really helped to heighten the role of the podiatrist in the treatment of musculoskeletal disorders of the foot. Many (Hicks 1953, Manter 1941, Sutherland

and Hagy 1972, Schwartz et al 1964, Joseph 1954, Wright et al 1964) to name only some of the references used by Root et al (1971, 1977) had previously described the joints of the foot, and the movement of them during walking. Root et al (1971, 1977) were the first to convert this information into a framework that assisted clinical practice (surgical and orthotic practice in the United States of America) which was then integrated into practice worldwide.

The Root et al (1971, 1977) description proposed a series of hypothetical concepts about the “ideal” or “normal” foot, and the relationship between the biomechanical characteristics of a foot and the cause of injury. Root et al (1971, 1977) hypothesised that there is a mechanically “normal” foot. They described how through using a series of different static examinations, the joints of the foot would be able demonstrate specific angles, or range of motion during the gait cycle. Any foot that did not demonstrate these specific parameters was considered to have a structural deformity. This foot would be classified as abnormal, and would be pre-disposed to injury.

Many (McPoil and Hunt 1995, McPoil and Cornwall 1994, Pierrynowski and Smith 1996, Menz 1995, Keenan and Bach 2006) have suggested that there are several key difficulties with the Root et al (1971, 1977) description. Such as the poor reliability, questionable validity and predominantly unknown accuracy of it, and yet it remains at the forefront of podiatric biomechanics internationally. This is because although these investigations have reported some of the problems with Root et al (1971, 1977), there are many limitations of these new investigations. They have either just focused on an individual aspect of Root et al (1971, 1977) (for example the reliability of an individual examination), have used poor experimental design when conducting an investigation, or they have used too fewer participants, and therefore can only hypothesise on what could be the normal or abnormal foot. The information from these investigations has also so far failed to be converted into something that can be used in clinical practice by podiatrists, or other allied health professionals for treating deformity or injury of the foot. Therefore, as described by Hay et al (2008) clinicians will continue to use what they trust and perceive to work, until there is a significant amount of evidence to suggest a change in their current practice.

The investigation in this thesis aims to provide a detailed test of the Root et al (1971, 1977) description, and challenge the scientific credibility of the concepts underpinning podiatric biomechanical education, and clinical practice.

1.2 Thesis structure

Chapter 2 forms the basis of the literature review, and is a critique of the Root et al (1971, 1977) description of the normal and abnormal foot. This includes an appraisal of the literature used by Root et al (1971, 1977), as well as the results from more recent investigations. These have provided new descriptions about the function of the foot using kinematic, kinetic, electromyographical and plantar pressure data. From this literature review, two research questions were posed and within these a series of hypotheses for one of the research questions were developed. For the other research question, statements from Root et al (1977) were tested. which are later referred to within this thesis as “Root et al hypotheses”. These hypotheses and Root et al hypotheses are described in Chapter 3. Each hypothesis represents a key feature of the Root et al (1977) description of the proposed relationship between the static based biomechanical assessment of the foot, and the kinematic motion of the joints of the foot during the gait cycle. Each Root et al hypothesis represents a key feature of the Root et al (1977) description of the function of the foot during the gait cycle. To determine the most suitable method for quantifiably describing the kinematic function of the normal foot using a skin based retro-reflective marker design, a separate literature review is presented at the end of Chapter 3.

Two preliminary investigations were conducted and are described in Chapter 4. The first includes a study using the Delphi technique. This aimed to determine what static based biomechanical examinations of the foot described by Root et al (1971, 1977) are still used in clinical practice by podiatrists. This formed the basis for the protocol for the static based biomechanical assessment of the foot. The second is an inter-assessor reliability investigation using a subset of the examinations from the assessment protocol identified in the first preliminary investigation. These two investigations formed the basis for a manuscript that was accepted by peer review into the Journal of Foot and Ankle Research.

Chapter 5 describes the methods used in this investigation for the collection, processing, and analysis of data. It describes the protocol for each static biomechanical examination of the foot, the methods used for the measurement of the three-dimensional kinematic motion of the foot and leg and all statistical analysis conducted.

Chapter 6 presents the results and discussion of each hypothesis and statement described in Research Question 1 and 2. It also includes an overall description of the movement of each inter-segmental angle calculated within the foot. From these results it was possible to determine the overall conclusions, and clinical implications of this investigation and what future work is required.

CHAPTER TWO - BACKGROUND AND LITERATURE REVIEW

2.1 Chapter Overview

This chapter seeks to investigate the current understanding of foot biomechanics. It will focus on critiquing the biomechanical assessment of the foot protocol described by Root et al [(1971, 1977)] , and what they propose represents the movement and function of the normal or abnormal foot during walking. This review will take into consideration the literature used by Root et al [(1977)] and their interpretation of it. In addition, more recent investigations that have described new methods for measuring the kinematics, kinetics, muscle activity and plantar pressure of the foot and lower limb will be included.

This literature review is divided into three main sections. First, is a critique of what Root et al (1971, 1977) proposed represents the normal foot. The second is a critical review of Root et al (1977) description of the movement and function of the normal foot during walking. The third is a critique of the Root et al (1971) static biomechanical assessment of the foot protocol and whether the measurements obtained from this assessment protocol can predict the movement of the foot during walking.

The process for the conducting this literature involved two stages. First, identifying the literature used by Root et al (1971, 1977) in the text and reference sections. Secondly, all additional literature was researched using search engines which included PUBMED, OvidMedline, and Science Direct. The search terms used included either individually or separately: foot, ankle joint, subtalar joint, midtarsal joint, first metatarsophalangeal joint, rearfoot, midfoot, forefoot, medial, lateral, hallux, orthoses, asymptomatic, normal, intra-cortical bone pin, kinematic, plantar pressure, static examination, NCSP, RCSP, dorsiflexion, plantarflexion, inversion, eversion, abduction, adduction, forefoot varus, forefoot valgus, first ray, limb length discrepancy, range of, angle, gait cycle, foot model.

2.2 An overview of the Root et al (1971, 1977) description of the proposed normal foot

The publication of Root et al (1971, 1977) transformed foot and ankle biomechanics. Some suggest it is the most comprehensive and pioneering clinically based description of the biomechanical function of the foot to date (McPoil and Hunt 1995). Their model was based on their own clinical experience and the literature available at that time. Root et al (1971) proposed three features of their model (1) a protocol for the static biomechanical assessment of the foot, (2) a description of what they believed was the biomechanical function of the normal and abnormal foot during gait, and (3) a basis for the prescription of the functional foot orthosis. This together forms a complete "model" for a clinician to use in the assessment, and treatment of foot deformity. It continues to dominate clinical practice as well as the syllabus for under and post-graduate education of podiatrists and other allied health professionals. However, more recently some (McPoil and Cornwall 1994, Menz 1995, Pierrynowski and Smith 1996, Keenan and Bach 2006, Menz and Keenan 1997, Kirby 2000) have questioned the reliability and validity of many aspects of the Root et al (1971, 1977) description. Others (McPoil and Hunt 1995, Kirby 1989, Redmond et al 2006, Dananberg 2000, Perry 1992) have proposed new concepts for the biomechanical assessment of the foot and description of the function of the foot during walking.

2.2.1 The Root et al (1977) description of the "normal" foot

Root et al (1971, 1977) proposed that there is a "normal" foot, and feet that do not move or function the same as this proposed normal foot, are therefore abnormal. Root et al (1977) stated that it is possible to classify feet as normal or abnormal and predict how a foot will function dynamically through conducting a series of static biomechanical examinations. These aimed to determine the kinematic characteristics about the specific joints and functional units of the foot. Root et al (1977) describe only the joints (ankle, subtalar, midtarsal, first metatarsophalangeal joints) and functional units (first and fifth rays) they perceived to be important for normal function of the foot.

Root et al (1977) proposed that the kinematic characteristics of a joint are determined by many factors. These can include the shape of the articular surfaces, the position of the axis of rotation, the range of motion and osseous alignment of a joint relative to the supporting surface or other joints/functional units. The basis to how these mechanical characteristics determine the normal foot is outlined in the *"Biophysical criteria for normalcy"* (Root et al 1971, p.34). This is an eight stage criteria, which provides the clinician with a description and numerical basis to what are the "ideal" kinematic characteristics of a normal foot. This was proposed to ensure the foot will demonstrate *"maximum efficiency during static stance or locomotion"* (Root et al 1971, p. 34). However, Root et al (1977) concedes that the ideal osseous physical relationships between various parts of the foot are seldom seen clinically. Indeed, they accepted that minor variations from the strict criterion can occur and the foot can still be considered to be normal.

Agreeably, the concepts of “normal” and perfect alignment within the foot, and a neutral position of the foot are easy for clinicians to understand, visualise and utilise. This may partly explain why the Root et al (1977) description has remained at the forefront of podiatric biomechanical clinical practice for so long (Astrom and Arvidson 1995, Razeghi and Batt 2002). However, Root et al (1977) provided very little evidence that feet classified as normal when assessed using their examination protocol are symptom free, or more efficient. Many (Close et al 1967, Joseph 1954, McPoil and Hunt 1995) have reported that there is considerable inter-person variation in the shape and function of the foot, including feet that are symptom free. Therefore, Astrom and Arvidson (1995), Razeghi and Batt (2002) and Nester (2009) suggest that feet should be defined as normal based on presentation of symptoms rather than any foot alignment or movement criteria. if they

Root et al (1977) proposed that the function of the subtalar joint controls and initiates movement within the foot. They describe how during the contact phase, pronation of the subtalar joint will create skeletal flexibility within the foot and the foot will resemble a mobile adaptor. During midstance and propulsion, Root et al (1977) stated that supination of the subtalar joint will create skeletal rigidity within the foot, thus transforming it into a rigid lever. However, many investigations (McPoil and Cornwall 1994, Cornwall and McPoil 1999a, Leardini et al 2007, Kitaoka et al 2006, Simon et al 2006 and Hunt et al 2001a) using asymptomatic participants have reported that contrary to Root et al (1977), the subtalar joint or rearfoot remains pronated (everted) during midstance. This undermines what Root et al (1977) proposed is normal foot function.

2.2.2 The Root et al (1977) concept of abnormal compensation within the foot to accommodate for structural deformities of the foot

Root et al (1977) proposed that a foot is classified with a structural deformity if the measurements obtained from a static assessment of the foot indicate; limited motion, or incorrect alignment of any of the joints or functional units of the foot. In a foot classified with a structural deformity there will, according to Root et al (1977), be a change in the angulation of the foot relative to the supporting surface. Root et al (1977) proposed that the foot will always function to maintain a plantigrade contact with the supporting surface. Therefore, where there is a structural deformity the subtalar joint will compensate by pronating more during the contact phase, and or it will remain in a pronated position during midstance and or propulsion. This is in contrast to their hypothesised function of the normal foot as the subtalar joint is proposed to be supinate during these phases. This abnormal compensatory pronation of the subtalar joint is thought to increase skeletal flexibility within the foot when it should resemble a rigid lever. This proposed excessive mobility is thought to place excessive stress on the musculoskeletal system of the foot and leg resulting in the development of injury and deformity.

The majority of the structural foot deformities described by Root et al (1977) are single plane deformities (for example rearfoot varus/valgus and forefoot varus/valgus are all frontal plane deformities). However, pronation (or supination) of the subtalar joint is a tri-planar motion, and they propose it is the additional motion in the other two planes of pronation (or supination) that are the primary causes of musculoskeletal pathology. To reduce the amount of abnormal compensation by the foot, Root et al (1977) proposed that the construction of a functional foot orthosis will restore normal biomechanical function of the foot, leg and lower limb. However, McPoil et al (1988) and others (Buchanan and Davis 2005, Donatelli et al 1999, Garbalosa et al 1994 and Cornwall and McPoil 1999b) have identified the structural deformities described by Root et al in feet from asymptomatic cohorts. This questions whether these structural deformities are indicative of pathological movement of the foot or implicated in the cause of symptoms.

In addition to this, many investigations (Astrom and Arvidson 1995, Razeghi and Batt 2002, McPoil and Cornwall 1994, Hunt et al 2001a, Nigg 2001, Cornwall and McPoil 1999a, McClay 2000) have questioned whether pronation of the subtalar joint should be construed as a pathological movement. Indeed, many investigations (Leardini et al 2007, McPoil and Cornwall 1994, Hunt et al 2001a, Nigg 2001, Cornwall and McPoil 1999a, Kitaoka et al 2006, McPoil and Cornwall 1996a) have reported that the rearfoot remains in a pronated or everted position during midstance in asymptomatic feet.

2.2.3 Difficulties with the literature used by Root et al (1977)

At the time of publication, some of the investigations used by Root et al (1977) provided pioneering information about the kinematic function of the foot. However, the studies were predominantly crude kinematic studies with experiments which related little to the function of the foot during walking. This may help to explain Root et al (1977) poor understanding of the functional determinants of kinematic motion (Huson 2000, Nester et al 2001). There are many technical difficulties with the literature used by Root et al (1977). In particular, the investigations that have used statically mounted cadaver specimens (Hicks 1953, Manter 1941, Close et al 1956, Root et al 1966, Elftman 1960, Ebisui 1968, Inman 1976) present many experimental problems. Nester et al (2001), Nester and Findlow (2006) and Tweed et al (2008) describe how the constraints of these experiments would make it very difficult to represent the function of the foot during walking. For example, as demonstrated by Figure 2.1 and 2,2 the cadaver specimen foot was either secured to a wooden board under the foot (as used in Hicks (1953)) or the calcaneus was clamped to the supporting apparatus (as used in Manter 1941, Close et al 1956 and Root et al 1966). Therefore, any movement of the foot would only be possible through manual manipulation and be unable to represent the effect different gait cycle events such as heel lift have on function of the foot. Vogler and Bojsen-Moller (2000) proposed that these investigations would be unable to simulate the effect body weight has on the mechanics of the foot. This is because the foot was amputated above the ankle joint and no loading was applied through the foot. Vogler and Bojsen-Moller (2000) suggest that the weight bearing status of the foot can significantly affect the position of the axis of rotation and the range of motion available at the joints of the foot. Therefore, questioning the validity of Root et al (1977) assumption that the static non-weight bearing foot has the same kinematic characteristics as the weight bearing foot during walking.

The focus of these static cadaver investigations was to either discuss the shape of the different bones of the foot (Elftman 1960 and Laidlaw 1905), or to determine the position of the axis of rotation at the joints of the foot (Hicks 1953, Manter 1941, Inman 1976, Close et al 1956). Tweed et al (2008) stated that the experimental methods used in these investigations would be scientifically unacceptable today. For example, the placement of pins and rods to measure joint motion is highly error prone and is unable to accurately represent the joint being measured.

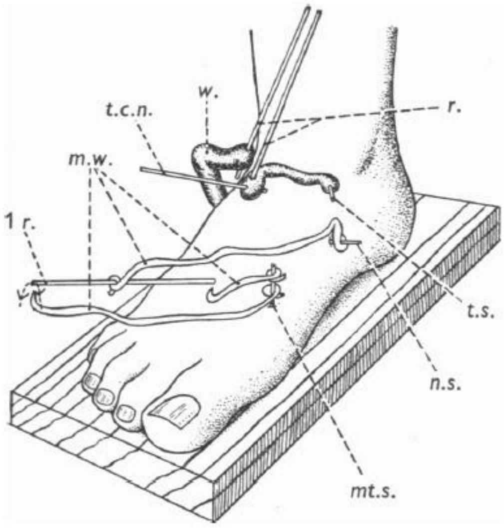


Figure 2.1: Image adapted from Hicks (1953)

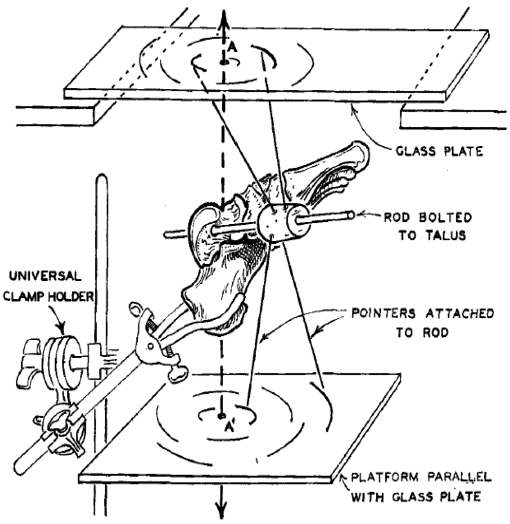


Figure 2.2: Image adapted from Manter (1941)

The position of the axis of rotation is described by Root et al (1977) as the key determinant for how joints move. For example, when referring to the first ray, Root et al (1977) describe how: *"The shape of the bones comprising the joints of the first ray determine its direction of motion and the position of the axis of first ray motion"* (Root et al 1977, p.48). However, Nester et al (2001) suggest that it is incorrect to use the axis of rotation of a joint as the main determinant for the calculation of the range of motion. This is because it is not a physical or anatomical entity as Root et al (1977) appears to propose. Nester et al (2001) describe how the axis of rotation at a joint should instead be viewed as a kinematic parameter. This is this then used to describe the rotation of one rigid structure relative to another rigid structure. Vogler and Bojsen-Moller (2000) and Huson (2000) describe how there are other important factors that contribute to the cause and control of joint motion. These include ligaments, muscle force, gravitational force and ground reaction forces (Vogler and Bojsen-Moller 2000 and Huson 2000). These are all largely neglected by Root et al (1977). The use of dynamic cadaver models by Nester et al (2006) and Sharkey and

Hamel (1998) offer updated versions of these fundamental studies used by Root et al (1971, 1977). They have, for example, applied loading onto the foot so as to simulate the near normal behaviour of the foot during walking.

Huson (1991), Huson (2000) and Rockar (1995) agree that the removal of soft tissue structures such as muscles and ligaments from the cadaver specimens allowed easier access to the different bones within the foot. However, they all emphasise that their removal will directly affect the range and direction of motion available at the joints of the foot. Root et al (1977) provided a poor description of the function of ligaments. They state that they are only important in the control of joint movement when the joint reaches the limit of its range of motion available. Extensive dissections of the ankle and subtalar joints by Leardini et al (2000) and Harper (1991) demonstrate that ligaments are essential for controlling the movement of at the extremes of joint motion. They are also vital for guiding the movement and maintaining the stability of each joint during its normal articulation, something Root et al (1977) fails to include.

Root et al (1977) does include a relatively in depth description of the function of the intrinsic and extrinsic muscles of the foot, which is largely based on the seminal work of Basmajian (1974). However, Root et al (1977) appears to propose that the function of a muscle is assumed to be solely dependent upon the position of the axis rotation at a joint. When describing what rotation occurs, Root et al (1977) only described the movement around the axis of rotation rather than how a joint articulation responds to muscle activity. Klein et al (1996) describe how there are other factors that determine the effect a muscle has on the movement of a joint. These include the strength of the muscle, the pathway of the muscle, and the tendinous insertion of it relative to the position of the joint axis, which determines the moment arm.

Inman (1976) stated that another potential difficulty with the use of cadaver specimens is the preservation of them. Cadaver specimens used in Close et al (1956), Hicks (1953), Manter (1941) and Inman (1976) were preserved in glycerine. Inman (1976) reports that this can affect the smoothness of the articular surfaces, the malleability of any residual soft tissue structures and the movement of the joints is highly sensitive to the position of them at the time of embalming. More recently, investigations such as Siegler et al (1988) and Nester et al (2006) have used cadaver feet freshly frozen on amputation and then thawed prior to the start of the investigation. This should provide a better representation of how the bony and soft tissue structures function in a foot.

One of the key investigations used by Root et al (1977) to describe the movement of the ankle and subtalar joints during walking is Wright et al (1964). However, there are numerous difficulties associated with this investigation that question the use and validity of the results obtained. Wright et al (1964) used potentiometers to measure the range of motion around the axis of rotation at the ankle and subtalar joints during the gait cycle. These potentiometers were hypothesised to be positioned directly over the axis of rotation at either joints. However, the reliability and validity of potentiometers is dependent on the accuracy of their placement. Any displacement of the potentiometer from the axis of rotation of the joint measured could result in motion being recorded as that joint’s movement, when in fact it is representative of the movement of another joint. The equipment design included a plaster cast that encased the entire lower leg and rigid shoes. These were designed to minimise any movement of the joints of the foot other than the ankle and subtalar joints. This would undoubtedly affect the walking pattern of the participant.

There was also only one participant used by Wright et al (1964). This may explain why Root et al (1971, 1977) stated such precise values, therefore implying that all feet will function the same. However, many recent investigations (Leardini et a 2007, DeMits et al 2012, Halstead and Redmond 2006, Lundgren et al 2007, Arndt et al 2004) have reported that there is large inter-participant variation in the movement of the joints of the foot. This would suggest that it is not possible to expect all feet to function and move exactly the same (Astrom and Arvidson 1995, Razeghi and Batt 2002, Nester 2009).

A further issue is the use of video, motion capture analysis, and force and pressure plate analysis was in its infancy in the majority of the literature used by Root et al (1977) (Close et al 1956, Levens et al 1948, Sutherland and Hagy 1972, Schwartz and Heath 1937, Schwartz et al 1964, Stott et al 1973, Schwartz and Heath 1947). The accuracy of the video systems and the placement of the cameras in some investigations (Levens et al 1948, Sutherland and Hagy 1972) appear to have contributed to the large error incurred.

Force and pressure plate analysis which describe loads applied to the foot were limited by the relatively basic instruments used. Schwartz and Heath (1947) placed pressure sensitive discs onto the plantar aspect of the foot, which may have affected the movement of the foot and altered the proprioception feedback between the foot and the supporting surface. This would ultimately change the walking pattern of the participant being tested. Stott et al (1973) and Schwartz et al (1964) used a pressure or force platform which was not large enough for the length of the foot. Therefore, the participant had to position their foot differently on the platform each time in order to create a complete description of the load applied to the foot. This is neither a reliable or valid measurement because sections of the foot may accidently not be measured and the data recorded is also not indicative of the participants usual walking pattern.

2.2.4 The joints of the Root et al (1977) description of the "normal" foot

The Root et al (1971, 1977) description provides a detailed description of some of the joints of the foot that they perceived were the most functionally important, these are reviewed below.

The subtalar joint

The subtalar joint consists of the bony articulation between the superior surface of the calcaneus and the inferior surface of the talus (Root et al 1977, Manter 1941, Hicks 1953 and Shephard 1951 and Rockar 1995). Root et al (1977) refers to Manter (1941) who stated that the subtalar joint axis is angled 42° from the transverse plane and 16° from the sagittal plane. It passes from the lateral, plantar and posterior aspect of the heel towards the anterior, dorso-medial aspect of the talus. Root et al (1977) proposed that there is pronation and supination around this axis, the requisite motions that represent either differ depending on the weight bearing status of the foot. Although the investigations (Hicks 1953, Close et al 1956, Manter 1941, Shephard 1951) referred to by Root et al (1977) are in agreement with what motion constitutes pronation and supination. They differ in their description of the articulation of the talus and calcaneus, and Root et al (1977) description is also different to theirs.

Hicks (1953), Shephard (1951), Root et al (1966) and Root et al (1977) describe the articulation of the talus upon the calcaneus as hinge like. This indicates that the movement is entirely rotational and does not include translation. However, Hicks (1953) and Shephard (1951) were describing the talo-calcaneal-navicular joint, and not solely the talo-calcaneal joint. Siegler et al (1988) proposed that the talo-calcaneal joint cannot function as an "ideal" hinge like joint with a fixed axis of rotation. This is because of its complex tri-planar motion and strong coupling mechanism with the ankle joint. This is similar to Manter (1941) who described the spiral like articulation of the talus upon the calcaneus, which infers it is a helical type joint.

Root et al (1971, 1977) proposed that the calcaneus will move relative to the talus in all three planes of motion to display open chain pronation (dorsiflexion, eversion and abduction), or open chain supination (plantarflexion, inversion and adduction) when the subtalar joint is examined non-weight bearing. In the normal foot, they suggest that subtalar joint should display a 2:1 ratio of frontal plane motion with two-thirds inversion and one third eversion. However, Weiner Ogilvie et al (1997) and Diamond et al (1989) when following the Root et al (1971) protocol did not find any evidence to support a 2:1 ratio.

When the foot is weight bearing, Root et al (1977) proposed that the subtalar joint will display closed chain supination and pronation. However, Root et al (1977), referring to Steindler (1929), proposed that the calcaneus will only move in the frontal plane and the talus will articulate upon the calcaneus in the sagittal and transverse planes. Therefore, Root et al (1977) advocated using the frontal plane movement of the calcaneus to represent the range of pronation and supination at the subtalar joint. This is because it is not possible to measure the movement of the talus as it is enclosed within the malleolar mortise. However, Steindler (1929) was actually pertaining to the plantarflexion and medial deflection of the talus in a pes valgus foot type. This could be construed as an abnormally pronated foot rather than the motion of pronation in a normal foot. The observations by Steindler (1929) are in agreement with Kido et al (2011), who reported that the calcaneus was more dorsiflexed and everted relative to the talus in feet classified as symptomatic flatfoot deformity (pes valgus), than feet classified as asymptomatic or normal. This suggests that the Root et al (1977) description of the movement of the subtalar joint is not an accurate representation of the asymptomatic or normal foot.

Additional factors that affect the movement of the subtalar joint which are not accounted for by Root et al (1977)

Rockar et al (1995) describe how ligaments and muscles that surround the subtalar joint are important for determining the motion available and position of the joint. Rockar (1995) and Harper (1991) state that the ligaments surrounding the subtalar joint help to form its fibrous joint capsule. These are essential for uniting the talus and calcaneus together so to control and guide the movement of this joint. Hunt et al (2001) and Rockar (1995) describe how the extrinsic muscles of the foot are major contributors to the movement of the subtalar joint and the function of the foot as a whole. Muscles such as tibialis anterior and tibialis posterior are key supinators of the subtalar joint, and peroneus brevis and peroneus longus are key pronators of the subtalar joint. However, most muscles and ligaments were removed in the experiments by Hicks (1953), Manter (1941), Root et al (1966) and Shephard (1951). Therefore, Root et al (1977) cannot describe how they contribute to the movement of the subtalar joint.

The accurate measurement of the movement of the subtalar joint during walking is inherently difficult. First, it is not possible to measure the movement of the talus without invasive methods such as intra-cortical bone pins (as used in Nester et al 2006, Lundgren et al 2007). Second, the Root et al (1977) proposed measurement using a bisection line drawn onto the posterior calcaneus has been described by Menz (1995) and others (Menz and Keenan 1997, Keenan and Bach 2006, Picciano et al 1993) as either unreliable or invalid.

More recently, many ((Leardini et al 2007, Hunt et al 2001, Moseley et al 1996, Cornwall and McPoil 1999, Rattanaprasert et al 1999, MacWilliams et al 2003, Nester et al 2007, Kitaoka et al 2006, Carson et al 2001) have used skin mounted markers to measure the movement of the calcaneus in the sagittal, frontal and transverse planes relative to the tibia. This method describes the movement of the subtalar and ankle joints together. The results from these investigations indicate this method is both reliable and as sufficiently accurate as possible when using skin surface mounted markers to measure this region of the foot. Siegler et al (1988) suggest that because the ankle joint functions predominantly in the sagittal plane and the subtalar joint functions predominantly in the frontal plane then the movement of the calcaneus in these planes relative to the tibia can be attributed to either joint. The measurement of the movement of the calcaneus in the frontal plane relative to the tibia also appears to comply with Root et al (1977). They describe how at the subtalar joint, the calcaneus will move in the frontal plane relative to the talus and tibia when weight bearing.

The neutral position of the subtalar joint

One of the key aspects of the Root et al (1977) description is the proposed importance of the neutral position of the subtalar joint. It was proposed that the subtalar joint is in a neutral position when it is neither pronated, nor supinated. Many of the static examinations described by Root et al (1971) involve positioning the subtalar joint into a neutral position as the starting position before moving the foot or measuring the alignment of the different joints or regions of the foot. Root et al (1971, 1977) proposed that the subtalar joint controlled and dictated any abnormal compensatory movement of the foot. Therefore, placing the subtalar joint into a neutral position enabled the clinician to determine if there is a structural deformity of the foot, rather than observing the resultant compensation of the foot.

Root et al (1977) stated that in the normal foot, the subtalar joint should be in a neutral position in bipedal standing which can be measured in the examination of Neutral Calcaneal Stance Position (NCSP). During walking, Root et al (1977) proposed that in the normal foot the subtalar joint will pass through its neutral position just prior to heel lift during midstance. It was proposed that if the subtalar joint was not in a neutral position (0°) in NCSP it will remain in an abnormally pronated position during midstance.

It is largely unclear how Root et al (1977) derived the concept of the neutral position of the subtalar joint. McPoil and Hunt (1995) suggest that Root et al (1977) mis-interpreted Wright et al (1964) description of “neutral.” Wright et al (1964) was actually describing the relaxed standing position of the foot, and no joints were positioned into a neutral position as it was later described by Root et al (1971, 1977).

More recently, some have reported that the weight bearing and non-weight bearing examinations of the neutral position of the subtalar joint are not reliable (Menz 1995, Keenan and Bach 2006, Menz and Keenan 1997, Picciano et al 1993, Keenan 1997). Others investigations (McPoil and Cornwall 1994, Pierrynowski and Smith 1996, Menz 1995, McPoil and Cornwall 1996a, Keenan 1997) have reported that there is little relationship between the results of these static examinations and the dynamic function of the foot during walking. This will be discussed in further detail in Section 2.3.

The ankle joint

The ankle joint consists of the articulation of the talus with the distal aspects of the tibia and fibula (Hicks 1953, Root et al 1977, Wright et al 1964, Leardini et al 2000, Lundberg et al 1989, Inman 1976, Arndt et al 2004). Previous and relatively basic descriptions (Root et al 1977, Hicks 1953, Barnett and Napier 1952, Wright et al 1964) construed the ankle joint to represent a simple hinge joint. It was proposed to have either a single fixed joint axis that passed medial to lateral through the talus (Root et al 1977 and Wright et al 1964), or an axis that angulation changes depending if the ankle joint is plantarflexing or dorsiflexing (Hicks 1953 and Barnett and Napier 1952).

However, Inman (1976) stated that no single axis could be established at the ankle joint. Inman (1976) reports that when the tibia was fixed and the talus was allowed to move, the talus could not remain in contact with all articular surfaces of the joint suggesting that the axis is moving with ankle joint motion. However, Inman (1976) also disagrees with Barnett and Napier (1952) and Hicks (1953) as the substantial technical difficulties associated with these investigations question the basis for their description of a moving axis. Inman (1976) stated that the compressive forces applied by the few residual tendons in Hicks (1953) investigation would be insufficient enough to force the articular surfaces together. This could create un-natural movements between the talus and malleolar mortise, artificially changing the angulation of the joint axis.

Root et al (1977) proposed that the position of the joint axis and the shape of the articular surfaces of the ankle joint allow predominantly sagittal plane motion. Transverse plane rotation at the ankle joint was considered in-significant to the function of the foot during walking. However, Inman (1976), Siegler et al (1988) and Lundberg et al (1989c) propose that the ankle joint does not function as an "ideal" hinge like mechanism. This is because of the complex nature of the articulation which includes sagittal, frontal and transverse plane motion. Inman (1976) described how the tri-planar rotation of the talus within the malleollar mortise is an integral part of the normal function of the foot and necessary to dissipate rotation forces from the tibia. This is in agreement with Nester et al (2003) and Lundberg et al (1989c), who both reported that there is a large range of transverse plane motion available at the ankle joint which is of similar range to that displayed at the subtalar joint. Nester et al (2003) concluded that the ankle joint plays a key role in the transfer of transverse plane rotation of the leg. This is a role Root et al (1977) assumes occurs primarily at the subtalar joint.

Additional factors that affect the movement of the ankle joint which are not accounted for by Root et al (1977)

Siegler et al (1988), Close et al (1956) and Leardini et al (2000) describe how the surrounding ligaments of the ankle joint are essential for maintaining the stability of the ankle joint, and guiding the articulation of this joint. However, these structures are largely ignored by Root et al (1977), and instead osseous geometry is assumed to be the main determinant of ankle joint motion. Stormont et al (1985) reports that the articular geometry of the ankle joint is responsible for controlling only 30% of the stability of the ankle joint when it is moving in the transverse plane. The remaining 70% is controlled by the surrounding ligaments and muscles. Leardini et al (2000) and Leardini et al (1999) describe how ligaments placed posterior, medial and lateral are essential for guiding the passive motion of the ankle joint and helping to contain the talus within the malleolar mortise (Leardini et al 2000).

The midtarsal joint

Root et al (1977) proposed that the midtarsal joint consists of two separate articulations; the talo-navicular joint and the calcaneo-cuboid joint. The main resource used by Root et al (1977) to describe the midtarsal joint is Manter (1941), who proposed that there are two axes of rotation; an oblique and longitudinal axis. Movement around the oblique axis was proposed to consist of only transverse and sagittal plane motion. This is because it is angled 52° from the transverse plane and 57° from the sagittal plane. Movement around the longitudinal axis was proposed to consist of predominantly frontal plane motion, because it is angled 15° from the transverse plane and 9° from the sagittal plane. However, Root et al (1977) proposed that there is triplanar (pronation and supination) motion around each axis which does not comply with Manter (1941) description.

Nester et al (2001) and others (Nester and Findlow 2006, Huson 2000, Tweed et al 2008) describe how the idea of a two axis model of the midtarsal joint has created much debate in the literature, and has greatly contributed to the overall misunderstanding of this joint. Huson (2000) described three key difficulties with the two axis model of the midtarsal joint. First, tarsal motions are spatial motions, therefore these joints will display all three planes of motion and function similar to a ball and socket joint. Second, Root et al (1977) proposed that there is a combined rotation about both axes of the midtarsal joint which would instigate a concurrent shift between the navicular and cuboid. However, Huson (2000), Tweed et al (2008) and Elftman (1960) state that this appears to not be possible, because there is a strong syndesmosis like connection between these two bones. Third, Huson (2000) stated that there is no evidence to support that axes representing the same or different directions of motion are indicative of rigidity, or limited motion.

To describe the movement of the midtarsal joint during walking, Root et al (1977) incorrectly focused on the rotation around the oblique and longitudinal axes. Therefore, failing to describe the actual movement of the talo-navicular and calcaneo-cuboid joints. More recently, the measurement of the movement of the midfoot during walking has either described the movement of the cuboid and navicular together (Leardini et al 2007, Jenkyn and Nicol 2007, Simon et al 2006, MacWilliams et al 2003, Nester et al 2007), or separately (Nester et al 2006, Blackwood et al 2005, Lundgren et al 2007) relative to the talus and calcaneus. None of these have adopted the two axis model of the midtarsal joint and also choose to describe this region of the foot as the “midfoot,” and not the midtarsal joint.

Additional factors that affect the movement of the midtarsal joint which are not accounted for by Root et al (1977)

Root et al (1977) description of the movement of the midtarsal joint focuses on the structural alignment and congruency of the articulating surfaces. However, Vogler and Bojsen-Moller (2000) state that "*Geometry alone does not define the potential movements of the tarsal joints"* (Vogler and Bojsen-Moller 2000, p.112). They highlight how structures such as ligaments and muscles play key roles in controlling the function of the midtarsal joint. Vogler and Bojsen-Moller (2000) suggest that Root et al (1977) reliance on cadaver investigations which have removed the surrounding soft tissue structures may explain their focus on the articulating structures.

The first metatarsophalangeal joint

The first metatarsophalangeal joint consists of the articulation between the head of the first metatarsal and the base of the proximal phalanx of the hallux (Root et al 1977, Halstead and Redmond 2006, Nawoczenski et al 1999). There are also sesamoid bones that sit in the grooves of the plantar aspect of the first metatarsal. These are described by Root et al (1977) as vital structures to improve the articulation of the joint.

Root et al (1977) believed that in the normal foot there is only sagittal and transverse plane motion available at the first metatarsophalangeal joint due to the hinge like shape of the joint articulation. Although, a hinge like articulation indicates it is only one plane but here Root et al (1977) is proposing that there is bi-planar motion.

However, according to Root et al (1977) the motion of any clinical significance is in the sagittal plane.

The key reference used by Root et al (1977) was Joseph (1954), who had reported a mean range of 70° dorsiflexion at the first metatarsophalangeal joint in a non-weight bearing static examination. Root et al (1977) hypothesised that because the first metatarsophalangeal joint can dorsiflex to this in a static non-weight bearing examination, it will also be dorsiflexed to at least 65° at toe off. However, some (Halstead and Redmond 2006, Nawoczenski et al 1999, Simon et al 2006, Carson et al 2001) investigations have reported that in asymptomatic feet the first metatarsophalangeal joint is dorsiflexed only 35°-50°.

Additional factors that affect the movement of the first metatarsophalangeal joint which are not accounted for by Root et al (1977)

Ahn et al (1997) and Van Gheluwe et al (2006) highlight how Root et al (1977) failed to realise the role of ligaments and muscles in the control of first metatarsophalangeal joint motion. Ahn et al (1997) also emphasise how Root et al (1977) did not appear to account for the huge functional demands of this joint or the large shear and compressive forces transmitted onto it during propulsion. These can also significantly change the function of this joint and contribute to the cause of deformity. The majority of the literature used by Root et al (1977), such as Bingold and Collins (1950), perceives deformity of the first metatarsophalangeal joint to be caused by injury, rather than the actual function of the foot.

The Root et al (1977) description of the first ray

The first ray as described by Root et al (1977) is a functional unit that consists of the first metatarsal and the medial cuneiform which will articulate with the navicular around a single axis of rotation. The first ray will also articulate with the second metatarsal, except Root et al (1977) primary focus is the first metatarso-cuneiform-navicular articulation. Root et al (1977) refers to Hicks (1953) and Ebisui (1968) who state that the axis of rotation for the first ray passes through the mid-dorsum of the foot over the third metatarsal to the tuberosity of the navicular. Ebisui (1968) proposed that the first metatarsal will dorsiflex and invert, or plantarflex and evert relative to the medial cuneiform and there is no movement of the first ray in the transverse plane. However, the validity of the proposed position of the axis of rotation of the first ray by Hicks (1953), Ebisui (1968) and Root et al (1977) appears to be questionable. Lundgren et al (2007) reported that the range of sagittal, frontal and transverse plane motion of the first metatarsal relative to the medial cuneiform was similar across all planes of motion. For example, Lundgren et al (2007) reported that the first metatarsal moved in the sagittal plane 5.3° (SD=2.0°), frontal plane 5.4° (SD=1.0°) and transverse plane 6.1° (SD=1.1°) relative to the medial cuneiform during the stance phase of walking.

Additional factors that affect the movement of the first ray which are not accounted for by Root et al (1977)

Lee and Young (2001) and Glascoe et al (1999) describe how Root et al (1977) incorrectly stated that the anatomical shape of the base of the first metatarsal and distal aspect of the medial cuneiform solely determine the direction of motion. There is as similar to the other joints of the foot, little reference to the importance of the surrounding soft tissue structures. Lee and Young (2001) and Glascoe et al (1999) report that the plantar, dorsal and interosseus ligaments, and the intrinsic and extrinsic muscles of the foot that insert onto or around the first ray are very important for controlling the position and mobility of the first ray.

A further difficulty of the Root et al (1977) description of the first ray is the little reference to its articulation with the navicular, and its role in the support and the function of the medial longitudinal arch. Glascoe et al (2000) described how the medial longitudinal arch is crucial for the weight bearing stability of the foot after heel off. Hick (1953) proposed that the arch stability is maintained by the windlass mechanism. This is a process by which plantarflexion of the first metatarsal, heel lift and hallux dorsiflexion increase the tensile forces in the plantar fascia. This is thought to increase the stability of the medial arch of the foot as body weight pivots around the forefoot.

The fifth ray in the Root et al (1977) description

Root et al (1977) proposed that the fifth ray consists of only the fifth metatarsal which will pronate and supinate around a tri-planar axis of motion. Root et al (1977) refers to Hicks (1953) who stated that the axis of rotation at the fifth ray passes through the superior-medial border of the foot at the first ray joint to approximately 1.5cm above and behind the styloid process of the fifth metatarsal. Root et al (1977) stated that the position of the axis of rotation is 20° from the sagittal plane and 35° from the transverse plane. This will allow a large range of sagittal and frontal plane motion, and a smaller range of transverse plane motion. Root et al (1977) proposed that motion in all three planes is clinically significant, although they conceded that the movement of the fifth ray is not well understood, and therefore their description is brief.

Nester et al (2006), DeMits et al (2012), Lundgren et al (2007) and MacWilliams et al (2003) who have measured the separate movements of the lateral and medial regions of the forefoot suggest that the fifth ray plays a key role in the function of the forefoot during the stance phase of the gait cycle. They all report that that the movement of the lateral region of the foot is greater in the sagittal, frontal and transverse planes than the movement of the medial region of the forefoot.For example, Lundgren et al (2007) reported that the total range of frontal plane motion of the 5th metatarsal relative to the cuboid is 10.4° (SD = 3.7°) and for the first metatarsal relative to the medial cuneiform it is only 5.4° (SD = 1.0°).

Additional factors that affect the movement of the fifth (and lesser rays) which are not accounted for by Root et al (1977)

The increased range of motion on the lateral aspect of the foot, compared to the medial aspect of the foot, could be because the respective bones on this side of the foot are able to move more freely as they are less confined by soft tissue structures. Muscles such as tibialis anterior, tibialis posterior and various intrinsic muscles within the foot such as abductor hallucis control the movement on the medial aspect of the foot but there are comparatively less soft tissue structures on the lateral aspect that could provide similar control.

2.2.5 A summary of the key points derived from a critical review of the Root et al (1971, 1977) description

1. Root et al (1971, 1977) described the movement of the joints of the foot independently from each other. However, the results from some (Huson 2000, Huson 1991, Wolf et al 2008, Pohl et al 2006, Lundgren et al 2007, Nester et al 2006) have demonstrated that the function of the foot is complex and there is inter-segmental co-ordination or coupling mechanisms between the joints of the foot..

2. Root et al (1977) focused on the osseous alignment and articulation of the joints of the foot. They fail to recognise the importance of soft tissue structures such as muscles and ligaments and how they contribute to the control of joint movement.

3. Root et al (1971, 1977) proposed that a foot classified with a structural deformity will demonstrate abnormal compensatory pronation and this will lead to the development of deformity and injury to the foot and leg. However, many (Garbalosa et al 1994, Buchanan and Davis 2005, Donatelli et al 1999, McPoil et al 1988) have demonstrated that asymptomatic individuals also have these structural deformities. This indicates that these structural deformities may not be a cause of injury.

4. A key feature of Root et al (1971, 1977) description is the hypothesised importance of the neutral position of the subtalar joint. However, many have reportedthat the measurement of the subtalar joint in NCSP is not reliable and there is no relationship between the measurements obtained from this examination and how the foot moves during the gait cycle.

5. Root et al (1971, 1977) proposed that the measurements obtained from a static biomechanical assessment of the foot will be able to predict how the joints of the

same foot will function during the gait cycle. However, many report that there is poor intra and inter-assessor reliability of most of the examinations from the Root et al [1971, 1977] assessment protocol. Furthermore, some have suggested that there is a not a strong relationship between the measurements obtained from these examinations and the movement of the joint examined during the gait cycle.

2.3 A critical review of the Root et al (1971, 1977) description of the proposed movement and function of the normal foot during the gait cycle

The publication of *"normal and abnormal function of the foot"* by Root et al (1977) provided the first definitive clinically orientated description of the biomechanical movement and function of the foot during walking. It remains at the forefront of podiatric biomechanics education and practice. However, advancements in technology have transformed gait analysis with improved methods for measuring the kinematics, kinetics, muscle activity and pressure under the foot during walking. This has provided new information about the function of the foot during walking which questions the Root et al (1977) description of the function of the normal or abnormal foot.

The following provides a critical appraisal of the description of foot motion during gait as proposed by Root et al (1977), with inclusion of more recent literature to support or refute the description by Root et al (1977).

The Root et al (1977) description of the function of the foot during the gait cycle

Root et al (1977) divides the gait cycle into two separate phases: the stance and swing phase. The description provided by Root et al (1977) focused almost entirely on the movement of the foot during the stance phase. The stance phase is divided by Root et al (1977) into three separate phases: the contact phase, midstance phase and propulsion.

There are two key features of the Root et al (1977) description that they hypothesised to represent the function of the normal foot during walking, these are:

1. The foot will represent a mobile adaptor during the contact phase, and transform into a rigid lever during midstance and propulsion.

2. The subtalar joint is the key functional joint of the foot that controls and initiates movement within the foot.

Quote 1: "*The foot is normally a mobile adaptor during the contact period. The pronated subtalar joint position provides skeletal mobility which enables the foot to compensate for, and adapt to, terrain variances and variances in postural position of the trunk and leg" (*Root et al 1977, p. 129*).*

Quote 2: *"The skeletal foot is converted from a mobile adaptor to a rigid lever necessary for propulsion"* (Root et al 1977, p. 129).

2.3.1 Contact phase

Root et al (1977) stated that the contact phase is defined from the initial contact of the heel with the supporting surface, to the initial plantigrade contact of the whole foot with the supporting surface. Root et al (1977) proposed that the foot will resemble a mobile adaptor during the contact phase. They described how pronation of the subtalar joint will create skeletal flexibility within the foot, as it allows the axes of the midtarsal joint to rotate in opposite directions. This was assumed to increase the flexibility of the foot, allowing the metatarsals to move more freely relative to each other and adapt to the supporting surface.

The subtalar joint

During the contact phase, Root et al (1977) proposed that in the normal foot the subtalar joint will pronate from its slightly supinated position at initial heel contact, until reaching the neutral position of the subtalar joint. It will then continue to pronate until the forefoot has made plantigrade contact with the supporting surface. Root et al (1977) referred to Wright et al (1964) who stated that the subtalar joint will pronate 4-6° during the contact phase. Root et al (1977) proposed that this movement of the subtalar joint is the 4-6° eversion of the calcaneus from its neutral position during this phase. However, Wright et al (1964) definition of pronation of the subtalar joint during the stance phase was a motion that o includes dorsiflexion, eversion, and abduction. This is representative of Root et al (1971, 1977) description of open chain pronation, not closed chain pronation. Wright et al (1964) also used the relaxed standing position of the foot to represent the zero degrees. The range of pronation described by Wright et al (1964) is therefore the total range of pronation during this phase. It is not from the neutral position of the subtalar joint as Root et al (1977) incorrectly interpreted.

In contrast, Leardini et al (2007) and others (Kitaoka et al 2006 and Cornwall and McPoil 1999, Moseley et al 1996, Rattanaprasert et al 1999) report that the range of calcaneal eversion relative to the tibia is much smaller than hypothesised by Root et al (1977). All these investigations report less than 3° eversion during the contact phase. The small range of motion during this phase is further highlighted by the results from Leardini et al (2007) and Cornwall and McPoil (1999a), who report that the calcaneus remained in an inverted position relative to the tibia at forefoot loading. For example, in Cornwall and McPoil (1999a) the calcaneus was inverted a mean of 2.5° relative to the tibia at initial contact It then everted only 1.5° during the contact phase to demonstrate a 1° inverted angle at forefoot loading.

All participants included in Leardini et al (2007) and others (Kitaoka et al 2006 and Cornwall and McPoil 1999a, Moseley et al 1996, Rattanaprasert et al 1999) were asymptomatic. These might reasonably be considered normal feet and thus the subtalar joint does not have to pronate as much as Root et al (1977) suggested to be symptom free.

Furthermore, the results from Arndt et al (2004), Leardini et al (2007), Cornwall and McPoil (1999), Kitaoka et al (2006), and Hunt et al (2001a) do not concur with Root et al (1977). First, Root et al (1977) stated that the calcaneus will not move in the sagittal and transverse planes relative to the talus during walking. However, the results of these investigations (Arndt et al 2004, Leardini et al 2007, Cornwall and McPoil 1999a, Kitaoka et al 2006, Hunt et al 2001a) suggest it can. Second, Arndt et al (2004) reported that the calcaneus dorsiflexed and abducted relative to the talus. This is in agreement with the movement of the subtalar joint as described by Wright et al (1964), but not Root et al (1977). In contrast, Hunt et al (2001a), Leardini et al (2007) and Cornwall and McPoil (1999a) reported that the calcaneus plantarflexed relative to the tibia. Although, the plantarflexion movement recorded by these investigations (Hunt et al 2001a, Leardini et al 2007 and Cornwall and McPoil 1999a) is hypothesised to be more representative of the overall movement of the ankle joint, than the subtalar joint during this phase.

In the transverse plane, Hunt et al (2001) reported that the calcaneus abducted relative to the tibia. While Cornwall and McPoil (1999a) and Kitaoka et al (2006) reported that the calcaneus adducted relative to the tibia. Although, Leardini et al (2007) and Lundgren et al (2007) reported that there were a similar number of feet from their cohort where the calcaneus abducted or adducted relative to the tibia (or talus) during the contact phase. Overall, there is large inter-participant variation in the movement of the subtalar joint in the transverse plane; which a mean value cannot represent. This suggests that is not possible to describe specific movement patterns that represent the normal foot, but rather a range of patterns are likely to be more representative of normal across the population.

Pronation of the subtalar joint, will according to Root et al (1977), allow internal rotation of the leg and knee joint during the contact phase. They proposed that the movement of the foot dictated the amount, and timing of rotation of the structures proximal to it. Root et al (1977) referred to Levens et al (1948) who reported 10.2° internal rotation of the tibia. This is similar to Preece et al (2007) who measured 12° internal rotation of the tibia. At the knee joint, Levens et al (1948) measured 3.5° of internal rotation during the contact phase, which is in agreement with Kadaba et al (1989) who measured between 3-4° internal rotation. Although, Preece et al (2007) argued that the cause of internal tibial or knee rotation remains undetermined within the literature and few agree with Root et al (1977). Preece et al (2007) proposed that a combination of proximal and distal torques which include muscle-tendon forces, ligamentous constraints and external forces such as ground reaction forces control, and initiate leg rotation.

The ankle joint

The ankle joint is described almost as a separate entity by Root et al (1977), and only the sagittal plane movement of this joint is discussed in detail. Root et al (1977) proposed that the ankle joint will plantarflex 10° from initial heel contact, to forefoot loading. Root et al (1977) referred to Sutherland and Hagy (1972), and Wright et al (1964) who both measured 8° of plantarflexion at the ankle joint during the contact phase. This is similar to Kitaoka et al (2006) and others (Moseley et al 1996, Cornwall and McPoil 1999, Arndt et al 2004, Lundgren et al 2007, Rattanaprasert et al 1999, Hunt et al 2001 and Leardini et al 2007) who have measured the movement of the calcaneus or talus in the sagittal plane relative to the tibia. They report between 6°-10° of plantarflexion. However, Kitaoka et al (2006), Arndt et al (2004), Leardini et al (2007), and Lundgren et al (2007) emphasised that there is large inter-participant variation in the range of plantarflexion, which ranges from 6° to 12°. This suggests that a range of angular values rather than a single value should be used to represent the normal foot.

The midtarsal joint

There are very few investigations used by Root et al (1977) that have measured the movement of the midtarsal joint and forefoot during walking. Instead. Root et al (1977) used investigations such as Schwartz and Heath (1937) and Schwartz et al

(1964) that have measured the pressure under the plantar aspect of the foot to infer the movement of the midtarsal joint and forefoot during walking. However, pressure data cannot directly describe the movement of the individual bones within the midfoot and forefoot. This may explain the predominately hypothetical description provided by Root et al (1971, 1977) about how the midtarsal joint moves during the gait cycle.

Root et al (1977) stated that during the contact phase the midtarsal joint will be supinated around its longitudinal axis through contraction of tibialis anterior. This will help to invert the forefoot, so that load can be transferred onto the lateral aspect of the forefoot. Conversely, Root et al (1977) stated that pronation of the subtalar joint, and contraction of extensor digitorium longus and peroneus tertius will pronate the midtarsal joint around its oblique axis. This will pronate the forefoot to aid the lowering of it to the ground. Hunt et al (2001b) and Murley et al (2009) reported in agreement with Root et al (1977) that these muscles are active, and do appear to help control the movement of the foot during the contact phase. Although, the timing of the peak activity of tibialis anterior was reported by Hunt et al (2001b) to be consistently at initial contact. It rapidly decreased before the end of the contact phase, However Murley et al (2009) reported that the tibialis posterior was active throughout the contact phase, with a peak of activity mid-way through the contact phase, indicating it is also controlling the movement of the subtalar joint.

Leardini et al 2007, DeMits et al 2012, MacWilliams et al 2003, Nester et al 2006, and Lundgren et al 2007 did not use a two axis model of the midtarsal joint. Instead, they either measured the movement of the individual bones within the midfoot or the midfoot as one rigid segment. However, they all reported that the midfoot everted (i.e. pronated) during the contact phase. In the sagittal and transverse planes there was large inter-participant variation in the direction of motion, but the range of motion was similar. For example, DeMits et al (2012) indicate that there were a similar number of feet in which the midfoot was plantarflexing, or dorsiflexing relative to the calcaneus during this phase. This suggests that the complexity of the articulations within this region of the foot make it difficult to state specific movements that should occur.

The forefoot

The Root et al (1977) description of the movement of the forefoot during the contact phase is inadequate. This is because the majority of the investigations used by Root et al (1977) that had measured the intricate kinematic movement of the forefoot were static cadaver investigations (For example: Hicks 1953, Manter 1941, Ebisui 1968). Therefore, these could only hypothesise on how the forefoot may move during walking. The majority of other investigations (Schwartz et al 1964, Wright et al 1964, Schwartz and Heath 1937) used by Root et al (1977) measured the movement of the forefoot during walking through plantar pressure measurements. However, these investigations only perceived the forefoot to be functionally important during propulsion, and therefore only describe in detail its movement during this phase.

Root et al (1977) proposed that the movement of the forefoot is dependent on the movement of the subtalar, and midtarsal joints during walking. If the movement of the subtalar joint and midtarsal joint was as Root et al (1977) described as normal, then the movement of the forefoot would also be normal. However, this suggests a simple deterministic coupling exists and fails to take into account other factors, such as ground reaction forces and terrain.

Root et al (1977) proposed that there will be skeletal flexibility within the forefoot during the contact phase, except there is no kinematic data presented to support this theoretical assumption. Agreeably, Blackwood et al (2005) reported that with eversion of the calcaneus, there is a greater range of sagittal plane motion of the first, third and fifth metatarsals, than when the calcaneus was in an inverted position. However, this experiment was conducted non-weight bearing using cadaver specimens. The results from DeMits et al (2012), Leardini et al (2007), Lundrgen et al (2007) and Nester et al (2006) indicate overall a relatively small and similar range of motion across planes of motion within the midfoot, and forefoot during the contact phase. This range of motion is also less, or similar to the range of motion of these regions of the foot during the midstance and propulsion phases. This questions the proposed idea that there is skeletal mobility within the foot during the contact phase.

The movement of the lateral forefoot is considerably greater than the medial forefoot during the contact phase. Nester et al (2006) and Lundgren et al (2007) reported that the medial forefoot (or first metatarsal) and lateral forefoot (fourth or fifth metatarsal) dorsiflexed, inverted, and adducted relative to the medial cuneiform, or cuboid during the contact phase. In contrast, using skin mounted markers Leardini et al (2007) reported that the whole forefoot, and DeMits et al (2012) reported that individually the medial and lateral forefoot (or whole forefoot) dorsiflexed, everted and adducted, then abducted relative to the midfoot during the contact phase.

2.3.2 Midstance Phase

Root et al (1977) stated that the midstance phase is defined from when the foot has reached plantigrade contact with the supporting surface to when the heel begins to lift from the ground. During the midstance phase, Root et al (1977) hypothesised that the primary function of the foot is to transform from a mobile adaptor into a rigid lever. This was proposed to create skeletal rigidity and stability within the foot which according to Root et al (1977) will ensure the foot is prepared for the functional demands of propulsion.

The subtalar joint

To create rigidity within the foot, Root et al (1977) referring to Wright et al (1964) stated that the subtalar joint throughout midstance, and just before heel lift itwill pass through its neutral position (0°). Root et al (1977) appeared to infer that if the subtalar joint passed through its neutral position it will ensure that it has displayed enough supination throughout midstance. Therefore, the foot will be sufficiently stable for the functional demands of propulsion. This is a defining feature of the Root et al (1977) description. It dominates the description of the function of the foot during walking, and defines the proposed relationship between the static and dynamic function of the subtalar joint . Pronation of the subtalar joint during midstance was described by Root et al (1977) as abnormal. It was proposed to be a cause of injury, or deformity because it would create flexibility within the foot when it should resemble a rigid structure. Root et al (1977) stated that:

"A normal foot does not pronate beyond the contact period." (Root et al 1977, p.137).

However, many (Leardini et al 2007, Pierrynowski and Smith 1996, Moseley et al 1996, Hunt et al 2001a, Cornwall and McPoil 1999a, McPoil and Hunt 1995, McPoil and Cornwall 1994, McPoil and Cornwall 1996a, Jenkyn and Nicoll 2007, Rattanaprasert et al 1999, Lundgren et al 2007, Arndt et al 2004) recent investigations have reported results that are in complete contradiction to Root et al (1977). First, the calcaneus remained in an everted position relative to the tibia, or talus during midstance. Second, that the peak angle of calcaneal eversion relative to the tibia occurred during midstance, and not at forefoot loading. Third, the calcaneus is everted at heel lift. All of these investigations (Leardini et al 2007, Pierrynowski and Smith 1996, Moseley et al 1996, Hunt et al 2001a, Cornwall and McPoil 1999a, McPoil and Hunt 1995, McPoil and Cornwall 1994, McPoil and Cornwall 1996a, Jenkyn and Nicoll 2007, Rattanaprasert et al 1999, Lundgren et al 2007, Arndt et al 2004) have used asymptomatic participants, suggesting that pronation of the subtalar joint during midstance is not a cause of injury or deformity. This questions the accuracy of what is proposed by Root et al (1977) to represent the normal foot.

There is some variation between different investigations in the timing of the peak angle of eversion during midstance. Moseley et al (1996), Kitaoka et al (2006), Rattanaprasert et al (1999) and Cornwall and McPoil (1999a) reported that the peak angle of calcaneal eversion relative to the tibia is 4° to 5° relative to the tibia between 50 % to 57% of the stance phase. While Jenkyn and Nicol (2007), and Hunt et al (2001a) described a greater and earlier peak angle of 7° calcaneal eversion relative to the tibia at 25%-30% of the stance phase. Pierrynowski and Smith (1996), McPoil and Cornwall (1996a) and McPoil and Cornwall (1994) also reported that the movement of the calcaneus in the frontal plane relative to the tibia during midstance did not intersect the angle of the calcaneus in NCSP, or RCSP. There is a more detailed critique of the proposed relationship between the static measure of the foot in NCSP, and the dynamic movement of the calcaneus during the stance phase of gait in section 2.4.1.

A definite trend in the pattern of motion described by these investigations (McPoil and Cornwall 1994, Leardini et al 2007, Pierrynowski and Smith 1996, Moseley et al 1996, Hunt et al 2001a, Cornwall and McPoil 1999a, McPoil and Hunt 1995, Jenkyn and Nicoll 2007 and Rattanaprasert et al 1999) was that no investigation reported a sudden change in the direction of motion. Root et al (1977) inferred that at the point of forefoot loading there will be a sudden change in the movement of the subtalar joint from a pronated position, to rapid re-supination. However, quite the opposite was described by all of these investigations (McPoil and Cornwall 1994, Leardini et al 2007, Pierrynowski and Smith 1996, Moseley et al 1996, Hunt et al 2001a, Cornwall and McPoil 1999a, McPoil and Hunt 1995, Jenkyn and Nicol 2007, Rattanaprasert et al 1999). They all reported a much more gradual eversion movement during the contact and midstance phases, and similar gradual inversion late in midstance, and throughout propulsion. A slower velocity of movement has been proposed by some (McClay 2000, Nigg 2001) to reduce the risk of injury. While sudden movement changes are hypothesised to be more traumatic; rather than the amount or direction of motion.

Murley et al (2009), Hunt et al (2001b), and Ivanenko et al (2004) reported that the peak activity of tibialis posterior, medial and lateral gastrocnemius was at 35% of the gait cycle, which co-insides with the timing of the peak angle of eversion. This indicates that in agreement with Root et al (1977) the function of these muscles are to exert a supinatory force on the subtalar joint. Although this also emphasises that contrary to Root et al (1977) if the subtalar joint had started to invert prior to this as Root et al (1977) proposed, then these muscles would be more active earlier in the gait cycle.

Root et al (1977) provided very little description about the movement of the subtalar joint in the sagittal and transverse planes during midstance. This is because they assumed that the range and pattern of frontal plane motion of the calcaneus would infer the dorsiflexion, and abduction movement of the talus upon the calcaneus. Although not measuring the movement of the talus directly, Cornwall and McPoil (1999a), Moseley et al (1996), Rattanaprasert et al (1999), Lundgren et al (2007), Arndt et al (2004) and Leardini et al (2007) all reported that the calcaneus dorsiflexed and adducted relative to the tibia during midstance. This indicates that contrary to Root et al (1977) the calcaneus can move in these planes when weight bearing. All investigations reported that the calcaneus adducted relative to the tibia between 4-5° during midstance.

The range of dorsiflexion reported by these investigations (Cornwall and McPoil 1999a, Moseley et al 1996, Rattanaprasert et al 1999, Leardini et al 2007, Hunt et al 2001a, Kitaoka et al 2006) is much larger than those (Lundgren et al 2007, Arndt et al 2004) that have measured the movement of the calcaneus relative to the talus. This strongly indicates that the movement of the calcaneus relative to the tibia is representative of the ankle joint.

The ankle joint

Root et al (1977) proposed that the ankle joint will begin to dorsiflex from just before forefoot loading and continue to dorsiflex throughout midstance. It will reach a peak angle of 10° dorsiflexion just prior to heel lift (Root et al 1977). In this position, Root et al (1977) stated that the tibia is dorsiflexed 10°, and this will directly predict the position of the ankle joint. Root et al (1977) stated that 10° of dorsiflexion is required during midstance to allow the leg and trunk to move in the sagittal plane above the foot. This motion would occur at the ankle so that the foot could remain in plantigrade contact with the supporting surface. However, the results from Sutherland and Hagy (1972) and Wright et al (1964), which are referenced by Root et al (1977), and more recent investigations (Kitaoka et al 2006, Moseley et al 1996, Cornwall and McPoil 1999a, Hunt et al 2001a, Leardini et al 2007 and Arndt et al 2004) indicate that Root et al (1977) over-estimated the angle of the ankle joint at heel lift. All report a dorsiflexed angle of between 5° to 8°.

There was also some inter-participant variation reported by these investigations. This indicates that it is not possible to stipulate a specific angle of dorsiflexion that represents the normal foot. For example, Arndt et al (2004) who measured the movement of the ankle joint using intra-cortical bone pins reported a mean peak angle of dorsiflexion of 7.3°. However, the peak angle of dorsiflexion ranged from 1.6° to 10.4° across the three subjects tested. This to a lesser extent is demonstrated by investigations measuring the movement of the calcaneus in the sagittal plane relative to the tibia.

Root et al (1977) stated that the cause of the heel to lift from the ground is primarily initiated by the contraction of the gastrocnemius and soleus. This will together flex the knee and plantarflex the ankle joint, so that the heel lifts from the ground. Agreeably, the results from Ivanenko et al (2004), Hunt et al (2001b) and Kadaba et al (1989) demonstrate that the medial and lateral gastrocnemius and soleus are active during midstance, with a peak of activity at 45% of the gait cycle, which is approximately the time of heel lift. Although, Hunt et al (2001a) and Perry (1992) suggested that the prolonged activity of the medial and lateral gastrocnemius from forefoot loading, and into the middle of propulsion indicate that these muscles are also essential for controlling leg rotation and stability during this period of gait. However, Root et al (1977) failed to discuss other factors extrinsic to the foot which have been suggested by Perry (1992). Such as the forward momentum of the upper limb, and trunk which function similar to a pendulum like system, these will propel the body forwards, and hence also initiate heel lift.

The midtarsal joint

Root et al (1977) stated that to create skeletal rigidity within the midfoot and forefoot, the midtarsal joint must pronate around both of its axes, and this will lock the forefoot against the rearfoot. Root et al (1977) described how: *"Locking of the forefoot against the rearfoot around the longitudinal axis is essential for normal propulsion"* (Root et al 1977, p.140). Root et al (1977) hypothesised that during midstance in the normal foot, the midtarsal joint will remain in a pronated position around its oblique axis, and it will pronate from its supinated position around the longitudinal axis. Root et al (1977) stated that the midtarsal joint will become fully pronated, or locked around both axes when the subtalar joint reaches, and passes through its neutral position.

Root et al (1977) described how supination of the subtalar joint, and ground reaction forces will change the alignment of the axes of the midtarsal joint. This will allow only a small area of congruous surfaces between the talo-navicular, and calcaneo-cuboid joints to be able to articulate together, therefore restricting the range of motion available. To maintain the stability within the midfoot and forefoot during midstance, they described how tension from ligaments encasing this area of the foot will create compression forces within the midtarsal joint. However, Root et al (1977) proposed that these compression forces only serve to hold the joint together, and it is the shape of the articular surfaces that determine the range of motion available. Vogler and Bojsen-Moller (2000) agree to some extent with Root et al (1977) and state that tarsal locking is dependent upon structures such as the surrounding ligaments, plantar fascia, peroneus longus and posterior tibial tendons. However, Vogler and Bojsen-Moller (2000) suggested that the surrounding ligaments in this region of the foot help to transfer the torsional moments from the surrounding bony architecture. Instead, the articular interfacing of the different bones is more important to ensure that they can accept these forces.

The proposed movement of the midtarsal joint during midstance as described by Root et al (1977) as dependent upon supination of the subtalar joint. However, many (Kitaoka et al 2006, Moseley et al 1996, Cornwall and McPoil 1999a, Hunt et al 2001a, Leardini et al 2007 and Arndt et al 2004) have reported that the calcaneus remained in an everted position relative to the tibia or talus during midstance. Root et al (1977) would classify these feet as abnormal. Root et al (1977) stated that there will be excessive mobility within the foot if the subtalar joint remains in a pronated position during midstance. This is because the midtarsal joint will remain in a supinated position around the longitudinal axis instead of pronating and "locking".

The results from Leardini et al (2007), Jenkyn and Nicol (2007), DeMits et al (2012) and Lundgren et al (2007) demonstrate that the midfoot dorsiflexed, everted, and abducted relative to the calcaneus during midstance. This would concur with Root et al (1977) description of pronation of the midtarsal joint during this phase, but it is contrary to how they describe the relationship between the subtalar and midtarsal joints. These investigations do not agree with Root et al (1977) that the movement of the midfoot will induce rigidity within the foot, or that the midfoot will be in a maximally pronated position at heel lift. This suggests, contrary to Root et al (1977), that rigidity within this region of the foot during midstance is not a pre-requisite for a foot to be symptom free. If the midfoot did lock against the calcaneus to immobilise the forefoot, there should be considerably less movement within these regions of the foot during midstance than during the contact phase. However, these investigations (Leardini et al 2007, Jenkyn and Nicol 2007, DeMits et al 2012 and Lundgren et al 2007) reported a similar range of sagittal, frontal and transverse plane motion of the midfoot relative to the calcaneus during midstance. In some planes motion was greater than that during the contact phase. There was also large inter-participant variation described by all investigations, with no consistent trend in the range or direction of motion. For example, the standard deviation band width across all graphs in DeMits et al (2012) includes bothdorsiflexion and plantarflexion, inversion and eversion and abduction and adduction.

The forefoot

The results from some (Leardini et al 2007, Jenkyn and Nicol 2007, DeMits et al 2012, Nester et al 2006 and Lundgren et al 2007) indicate that contrary to what Root et al (1977) proposed there is not skeletal rigidity within the forefoot during the midstance phase. This is because the range of sagittal, frontal and transverse plane motion of the medial and lateral regions of the forefoot (or the first and fifth metatarsals) relative to the midfoot (or the medial cuneiform and cuboid) is similar to the contact phase. This indicates, contrary to what Root et al (1977) proposed there is not skeletal rigidity within the forefoot during the midstance phase.

Nester et al (2006) reported that the first and fifth metatarsals dorsiflexed, adducted and everted relative to the medial cuneiform or cuboid. Arguably the range of motion is very small, perhaps inconsequential, with the first metatarsal dorsiflexing relative to the medial cuneiform only 2°. However, the range of sagittal plane motion between the fifth metatarsal and the cuboid is larger. It dorsiflexed 2.5° during the first half of midstance, and then plantarflexed the same amount during the second half of this phase. This is similar to the movement patterns reported by DeMits et al (2012), Simon et al (2006) and MacWilliams et al (2003). They describe how the first and fifth metatarsals (or the second to the fifth metatarsals (DeMits et al 2012)) dorsiflexed, everted and contrary to Nester et al (2006) abducted less than 5° for each plane of motion relative to the midfoot. This is also a similar range of motion to the contact phase.

2.2.3 Propulsion

Root et al (1977) stated that propulsion is defined from when the heel begins to lift from the ground to toe off. During propulsion, Root et al (1977) proposed that the normal foot will remain as a rigid and propulsive lever. This according to Root et al (1977) will ensure the foot remains stable as the heel lifts from the ground, and body weight is transferred onto the forefoot. Stability of the foot during this phase is described by Root et al (1977) as essential. This is so that the first metatarsophalangeal joint can dorsiflex sufficiently during the final stages of propulsion.

Agreeably, some (Hunt et al 2001, Sarrafian 1987, Bojsen-Moller 1979) have described the importance of stability during propulsion, particularly highlighting the role of the plantar fascia. However, they do not propose that the foot is rigid, and many (Lundgren et al 2007, Jenkyn and Nicoll 2007, MacWilliams et al 2003, Leardini et al 2007, Nester et al 2006) have reported a greater range of motion within the joints of the midfoot and forefoot during propulsion than the other phases of the gait cycle.

The subtalar joint

Root et al (1977) stated that during propulsion in the normal foot, the subtalar joint will supinate through its neutral position just prior to heel lift to be in a supinated position. It will continue to supinate until the final stages of propulsion where it will then pronate. Root et al (1977) stated that supination of the subtalar joint throughout propulsion is the integral mechanism for ensuring the foot remains a rigid and propulsive lever.

Wright et al (1964) described how the subtalar joint will supinate 4° around its axis of rotation during propulsion. However, Wright et al (1964) stated that this includes plantarflexion, inversion and adduction. This is again indicative of Root et al (977) description of open chain supination, not closed chain supination as Root et al (1977) is pertaining too.

In agreement with Root et al (1977), Lundgren et al (2007) and others (Kitaoka et al 2006, Hunt et al 2001a, Cornwall and McPoil 1999a, Jenkyn and Nicol 2007, Moseley et al 1996, Rattanaprasert et al 1999) reported that the calcaneus inverted relative to the tibia and talus during propulsion. However, the range of inversion measured appears to be dependent on the method of measurement, but it is still larger than that described by Wright et al (1964). Lundgren et al (2007), Nester et al (2006) and Arndt et al (2004) reported 5° of inversion, while Cornwall and McPoil (1999a), Moseley et al (1996), Hunt et al (2001a) and Leardini et al (2007) measured between 6°-10° inversion. Although, results from Lundgren et al (2007), Nester et al (2006) and Arndt et al (2004) indicate that the talus is also inverting relative to the tibia, and this movement would be included when measuring the calcaneus relative to the tibia.

All investigations (Cornwall and McPoil 1999a, Moseley et al 1996, Hunt et al 2001a, and Leardini et al 2007, Lundgren et al 2007, Nester et al 2006 and Arndt et al 2004) reported in agreement with Root et al (1977) that the calcaneus everted relative to the tibia during the final stages of propulsion. This is hypothesised by Huson (1991) and Root et al (1977) to help maintain the contact of the medial aspect of the foot with the supporting surface, and aid the dorsiflexion of the first metatarsophalangeal joint.

In the transverse plane, Moseley et al (1996), Leardini et al (2007) and Nester et al (2006) reported that the calcaneus adducted relative to the tibia or talus. In contrast Cornwall and McPoil (1999a) and Hunt et al (2001a) stated that the calcaneus abducted relative to the tibia during propulsion. There is also a considerable difference in the range of adduction, or abduction measured by these investigations. For example, Moseley et al (1996) reported 10°, while Leardini et al (2007) measured less than 4° adduction of the calcaneus relative to the tibia. However, a possible reason for the difference between these investigations maybe caused by inter-participant variation, which the mean values cannot convey. This is supported by Lundgren et al (2007), who reported no consistent trend between participants in the direction, or the range of transverse plane motion of the calcaneus relative to the talus and/or tibia. This variation between participants which are all asymptomatic suggests that contrary to Root et al (1977), feet that are symptom free, do not demonstrate precise movement patterns at some joints in the foot.

The ankle joint

Root et al (1977) proposed that the ankle joint will reach a peak angle of dorsiflexion at heel lift, and will then rapidly plantarflex. This is in agreement with Nester et al (2006), Arndt et al (2004), and Lundgren et al (2007) who reported that the talus and calcaneus began to plantarflex relative to the tibia from heel lift, and the range of plantarflexion during this phase is between 5°-10°.

However, the results from Moseley et al (1996), Cornwall and McPoil (1999a), Leardini et al (2007) and Hunt et al (2001a) indicate that the calcaneus continued to dorsiflex relative to the tibia during the initial stages of propulsion. There are also considerable differences between these investigations in the range of sagittal plane motion measured with Moseley et al (1996) reporting only 9° of plantarflexion while Hunt et al (2001a) reported a mean of 24° plantarflexion during propulsion.

The midtarsal joint

Root et al (1977) proposed that during propulsion in the normal foot, the midtarsal joint will supinate around the oblique axis, and remain in a pronated position around its longitudinal axis. This Root et al (1977) stated will maintain the stability within the foot, and allow for the transfer of weight across the forefoot from lateral, to medial. Agreeably, Nester et al (2006), Lundgren et al (2007), Leardini et al (2007) and DeMits et al (2012) reported that the midfoot (or navicular and cuboid) inverted relative to the calcaneus (or talus) during propulsion. Although, the midfoot plantarflexed and adducted to indicate overall supination of the midtarsal joint during this phase. With exception of Nester et al (2006), all investigations reported a definite trend in the movement of the midfoot during propulsion, which Root et al (1977) does not describe. During the first half of propulsion, there was minimal movement of the midfoot (or navicular and cuboid) across all planes of motion relative to the calcaneus (or talus). The mean value indicates less than 1° of motion. During the second half of propulsion, the midfoot rapidly plantarflexed, inverted and adducted relative to the calcaneus. All investigations (Lundgren et al 2007, Leardini et al 2007 and DeMits et al 2012) reported that there is considerable inter-participant variation in the range, and direction of motion; particularly in the sagittal and transverse planes. This suggests that it would not be correct to describe specific movement patterns of the midfoot, or of the bones within in it. Overall this emphasises that movement of this region of the foot is much more complex than Root et al (1977) hypothesised.

Forefoot

Root et al (1977) stated that the first metatarsophalangeal joint must dorsiflex to at least 65° during propulsion, and that this is dependent on the movement of the subtalar and midtarsal joints. If the movement of these joints is what they determine to be normal, then the movement of the forefoot will also be normal.

Supination of the subtalar joint during propulsion is described by Root et al (1977) as essential for aiding the function of the forefoot during this phase. This is because it will pronate the midtarsal joint around its longitudinal axis to maintain the rigidity within the forefoot. Simultaneously it will supinate the midtarsal joint around its oblique axis, and with plantarflexion and eversion of the first ray, it will allow for the transference of weight from lateral, to medial across the forefoot. This will help to maintain the first metatarsal head in contact with the supporting surface. However, results from Nester et al (2006), Lundgren et al (2007), DeMits et al (2012) and Leardini et al (2007) indicate that there is not skeletal rigidity within the forefoot during propulsion. They reported that there is a greater range of motion within and between the forefoot relative to midfoot during propulsion than the midstance or contact phases.

Schwartz et al (1964) stated that during propulsion the main weight bearing capacity of the forefoot is centralised onto the third metatarsal head. However, Huson (1991) suggested that this role is more likely to be provided by the second metatarsal. The second metatarsal is tightly connected to the tarsus, and this will allow it to hypothetically function similar to a spoke of a wheel, allowing the medial and lateral regions of the forefoot to rotate either side of it. Therefore, with inversion of the tarsus, Huson (1991) described how the second metatarsal will allow the third to fifth metatarsals to invert and dorsiflex relative to it. This is supported by kinematic data from Nester et al (2006), DeMits et al (2012) and MacWilliams et al (2003). In contrast, with inversion of the tarsus, Huson (1991) stated that the first metatarsal will plantarflex so to remain in contact with ground. This is also in agreement with the kinematic data reported by Nester et al (2006), Lundgren et al (2007) and Leardini et al (2007). To aid the contact of the first metatarsal with the supporting surface, Root et al (1977) described how the shape of the forefoot is important, again emphasising the structural shape of the foot rather than its function. The first metatarsal head is shorter than the second metatarsal head, and sesamoids which are commonly situated under the first metatarsal head help facilitate the movement of the underlying tendons in and around the joint which is in agreement with Shereff et al (1986).

The first metatarsophalangeal joint

Root et al (1977) proposed that the first metatarsophalangeal joint must be dorsiflexed to 65° at the end of propulsion. The tibia will be tilted forward from vertical by 45° and the ankle joint will be plantarflexed 20°, so the first metatarsophalangeal joint can and must dorsiflex to 65°. Root et al (1977) described how the movement of the first metatarsophalangeal joint during propulsion involves the fixation of the hallux to the supporting surface, and the proximal phalanx of the hallux will move to the dorsal and anterior aspect of the head of the first metatarsal. As the heel continues to lift from the ground, Root et al (1977) described how the first metatarsal must plantarflex against the base of proximal phalanx of the hallux.

This will continue until the maximum range of dorsiflexion at the first metatarsophalangeal joint is reached.

The key reference used by Root et al (1977) to describe the range of motion available at the first metatarsophalangeal joint was Joseph (1954). Joseph (1954) measured the range of dorsiflexion at the first metatarsophalangeal joint in fifty men using different non-weight bearing, and weight bearing static based examinations captured by radiographic imaging. Joseph (1954) reported that the first metatarsophalangeal joint dorsiflexed to 70° in a non-weight bearing static examination. As Root et al (1977) proposed that the results of a static examination can predict the dynamic function of the foot, this value is proposed by them to represent the angle of dorsiflexion of the first metatarsophalangeal joint during propulsion.

The majority of more recent literature report that the first metatarsophalangeal joint will dorsiflex to much less than 65° during propulsion. For example, Halstead and Redmond (2006) 36.9°, Nawoczenski et al (1999) 42°, Turner et al (2007) 29.2° (SD = 6.9°), Simon et al (2006) 48.0° and Carson et al (2001) 38°-40°. Simon et al (2006), Halstead and Redmond (2006), Nawoczenski et al (1999), and Turner et al (2007) also all reported that the first metatarsophalangeal joint plantarflexed towards the end of propulsion, and the peak angle of dorsiflexion was during propulsion and not at toe off. In contrast, Van Gheluwe et al (2006) measured 80°, and Hopson et al (1995) measured 64.5° angle of dorsiflexion at toe off. However, Hopson et al (1995) used two dimensional video analysis which lacks the accuracy of three dimensional analysis used by most of the other investigations afore-mentioned. . There are also no details provided by Van Gheluwe et al (2006) to explain the position of the foot used to represent the zero reference position. The position used may explain the considerably larger angle of dorsiflexion measured compared to the other investigations.

A key feature from the results of Joseph (1954) is the considerable inter-participant variation. This strongly indicates that stipulating a single angle to represent the normal range of dorsiflexion at the first metatarsophalangeal joint as Root et al (1977) proposed is not suitable. Joseph (1954) measured 100 feet (50 right) and reported standard error of the mean (SEM) values of = 3.4 for that examination. The standard deviation, and standard error of the mean results from Halstead and Redmond (2006) SD =7.9° (15 feet), Nawoczenski et al (1999) SEM=2.3 (33 feet), and Hopson et al (1995) SD=8.5° (20 feet) are similar to Joseph (1954), even though they have tested fewer numbers of feet and measured the movement of that joint during walking. Collectively these studies demonstrate the large variation in the kinematics of asymptomatic feet.

2.3.4 The Swing Phase

There is undoubtedly a much greater interest and emphasis on the movement of the foot and leg during the stance phase, both from a research and clinical aspect (Perry 1992). Root et al (1977) description of the kinematic movement of the foot during the swing phase is very brief. It proposed that the two key functions of the foot during the swing phase. These are to aid ground clearance through dorsiflexion at the ankle joint, and facilitate transportation of the foot and limb past the stance phase limb. The foot will, according to Root et al (1977) move at the subtalar joint during the swing phase. Root et al (1977) stated that the subtalar joint is supinated at toe off, and will immediately pronate for the first 10% of the swing phase. It will then begin to supinate for remainder of the swing phase, to demonstrate a slightly supinated position at initial contact, which is in agreement with the results from Simon et al (2006). However, in contrast Pierrynowski and Smith (1996) reported that the calcaneus remained in an inverted position relative to the tibia for the first 10% of swing phase, and then the calcaneus everted relative to the tibia for the remainder of the swing phase, before inverting just before initial contact.

According to Root et al (1977) during the first half of swing the midtarsal joint will pronate around its oblique axis. In the latter half of the swing phase, it will supinate around the longitudinal axis. Supination of the midtarsal joint around its longitudinal axis is as a result of the contraction of tibialis anterior. Agreeably, Ivanenko et al (2004) reported that the tibialis anterior is active during the swing phase, particularly at the start and end of the swing phase. Root et al (1977) stated that this muscle action will aid the dorsiflexion of the ankle joint, and supination of the foot, ready for initial contact. Jenkyn and Nicol (2007) proposed a simpler description of the movement of the midfoot during the swing phase. They suggested that the midfoot everted and adducted less than 5° relative to the calcaneus throughout this phase.

2.3.5 A summary of the key points derived from a critical review of the Root et al (1971, 1977) description of the function of the foot during the gait cycle

1. Root et al (1977) proposed that the foot will function as a mobile adaptor during the contact phase, and a rigid lever during midstance and propulsion. However, there is little evidence to suggest there is a difference in the skeletal flexibility between the contact, midstance. or propulsion phases.

2. Many authors have reported that the calcaneus everted relative to the tibia or talus during midstance. This indicates that contrary to Root et al (1977) the subtalar joint does not re-supinate from forefoot loading.

3. There is very little information about the kinematic function of the foot during the swing phase from both Root et al (1977), and the contemporary literature.

4. Root et al (1971, 1977) provided a poor description of the kinematics of the midfoot during the gait cycle. They use predominantly unsubstantiated and hypothesised ideas, which are not supported by more recent literature. For example, many authors have criticised Root et al (1977) description of a two axis model of the midtarsal joint. These have instead demonstrated that the movement of the midfoot is more complex, and that there is a considerable range of motion between the different bones of the midfoot which is integral to the function of the foot during the gait cycle.

5. Root et al (1971, 1977) provided a very poor description of the kinematics of the forefoot during the gait cycle. There is a lack of accurate literature evidence referred to by Root et al (1977) which described the kinematics of the metatarsals during the gait cycle. Their description is purely hypothesised, and it is not supported by the results from more recent investigations. For example, many have reported that there is a considerable range of motion between the fifth metatarsal relative to the cuboid/midfoot during the gait cycle, and yet Root et al (1977) provided no description of the movement of the fifth ray during walking.

6. The large inter-participant variation reported by most investigations when describing the movement of any of the joints in the foot in asymptomatic individuals indicates that there is not “a normal” foot. There is also no evidence to suggest that

the normal foot proposed by Root et al (1977) is symptom free or more efficient. However, the majority of more recent investigations have reported data from small cohorts, and are these unable to characterise the true extent of the inter-subject variation within an asymptomatic cohort. More research is required with larger cohorts of asymptomatic feet to establish a greater understanding of what can defined as the asymptomatic foot.

2.4. A critical review of the Root et al (1971, 1977) protocol for the static based biomechanical assessment of the foot, and whether the measurements from these examinations can predict the movement and function of the foot during the gait cycle

Root et al (1971, 1977) proposed that the measurements obtained from conducting their biomechanical assessment of the foot will be able to predict the movement and function of the foot during walking. Root et al (1977) stated that the joints of foot should demonstrate specific angles and ranges of motion to be classified as normal. If the manual movement of a joint in the foot indicates limited or excessive range of motion, or it is not positioned at a certain angle, they proposed that the foot be classified as having a structural deformity. Root et al (1977) described seven structural deformities. These are: rearfoot varus, rearfoot valgus, ankle joint equinus, forefoot varus, forefoot valgus, plantarflexed first ray and dorsiflexed first ray. Root et al (1977) stated that a foot classified with a structural deformity will function abnormally during walking. This will result in trauma and mechanical changes to the foot which will cause injury and deformity to the soft and bony tissues of the foot and leg.

The following provides a critical appraisal of the biomechanical examinations of the foot described by Root et al (1971, 1977). The examinations include:

- Examination of the frontal plane angle of the subtalar joint in NCSP and RCSP
- Examination of the range of frontal plane motion at the subtalar joint
- Examination of the range of dorsiflexion at the ankle joint
- Examination of the forefoot to rearfoot relationship
- Examination of the sagittal plane position mobility of the first ray
- Examination of the range of dorsiflexion at the first metatarsophalangeal joint.
- Examination of limb length

More recently, some (Redmond et al 2006, McPoil and Hunt 1995, Kirby 1989, Dananaberg 2000, Perry 1992) have presented new ideas or concepts in an attempt to challenge and replace the Root et al (1971, 1977) description. These include:

- The Foot Posture Index (Redmond et al 2006)
- The tissue stress model (McPoil and Hunt 1995)
- The sagittal plane theory (Dananaberg 2000, Perry 1992)
- The Kirby skive technique (Kirby 1989)

2.4.1 Examination of the frontal plane angle of the subtalar joint in NCSP and RCSP

The examination of the frontal plane angle of the subtalar joint when the foot is positioned in NCSP, and relaxed calcaneal stance position (RCSP) are commonly regarded as key examinations from the Root et al (1971, 1977) assessment protocol. To conduct these examinations the patient should be standing, and the subtalar joint of both feet placed in a neutral position. Root et al (1977) described specific guidelines for positioning the subtalar joint into a neutral position. They proposed that there will be several key observable features when the subtalar joint is in a neutral position. First, there will congruency of the medial, and lateral edges of the talus relative to the calcaneus. This means that neither the medial, or lateral edges of the talus should be palpable in front or below the medial and lateral malleoli. Second, the concavity on the lateral aspect of the foot should be parallel to the concavity of the lateral surface of the leg. Third, there should also be a straight line on the lateral aspect of the foot in the region of the calcaneo-cuboid joint.

To measure the frontal position of the subtalar joint in NCSP, Root et al (1977) stated that the clinician should palpate the medial and lateral surfaces of the calcaneus, and draw a bisection line on the posterior aspect of the calcaneus. This should be midway between the medial, and lateral surfaces of the posterior aspect of the calcaneus. The angle of the bisection line is then measured with a goniometer or tractograph. The foot is then allowed to resume its normal resting position which Root et al (1977) described as RCSP, and the bisection line is re-measured.

Intra- and inter-assessor reliability of the examination of the frontal plane angle of the subtalar joint in NCSP and RCSP

There have been numerous investigations (Keenan 1997, McPoil and Hunt 1995, Pierrynowski and Smith 1996, Keenan and Bach 2006 and Menz and Keenan 1997, Picciano et al 1993) that have reported the poor intra, and inter-assessor reliability of the examination of NCSP and RCSP. The main focus of the difficulties associated with this examination protocol is the drawing of the bisection line. Menz (1995) and others (Keenan 1997, McPoil and Hunt 1995, Keenan and Bach 2006, Picciano et al 1993 and Menz and Keenan 1997) have questioned the validity of using a bisection line drawn onto the posterior aspect of the calcaneus to infer the movement of the subtalar joint. Menz (1995) stated that this method of examination only has *"face validity"* (Menz 1995, p.61). This is because the bisection line does not truly bisect the frontal plane angle of the calcaneus. The error from soft tissue and skin movement, fat pad displacement, and even pen marker thickness can all contribute to an incorrect measurement of the bisection line. This is to some extent, outside of the controls of the clinician. Another factor, not often discussed, is the difficulty for a patient to remain in NCSP whilst standing. This is especially the case for specific patient groups (for example; the elderly, children, patients with severe foot deformities). The measurement precision Root et al (1971, 1977) required suggests that this could also be a key contributing factor to the reported variability in the examination.

There is quite a large difference between investigations in the level of intra, and inter-assessor reliability. While some (Keenan and Bach 2006, Picciano et al 1993) have reported poor to low reliability between assessors, others (Menz and Keenan 1997, Smith-Oricchio and Harris 1990) report moderate to very good reliability. The measuring devices used, assessor skill, and the number of assessors might explain these variations. However, Pierrynowski and Smith (1997), Pierrynowski et al (1996), Keenan and Bach (2006) and Menz and Keenan (1997) suggest that it is important to consider the results of the descriptive analysis.

Picciano et al (1993) reported very poor intra-class correlation coefficients (ICC) values for the examination of NCSP with ICC = <0.18 for intra-, and ICC = <0.15 for inter- assessor reliability. However, Picciano et al (1993) used only two in-experienced assessors and thirty feet were assessed in total. Keenan and Bach (2006), Menz and Keenan (1997) and Keenan and Bach (2006) all used experienced assessors and report marginally better reliability results. This indicates that an assessor's clinical experience may help to improve the reliability of this measurement. Although, there is still only moderate agreement between assessors. Keenan and Bach (2006) examined twenty-four participants which were examined by four experienced assessors and reported Pearson r (r) values of r = 0.335 for NCSP and r = 0.405 for RCSP. This is similar to Menz and Keenan (1997) who report for the examination of NCSP r = <0.639 for the measurement with an angle finder and r = <0.561 for the measurement with a digital goniometer.

The considerable inter-assessor variation in the measurement of NCSP (and RCSP) reported by these investigations (Picciano et al 1993, Keenan and Bach 2006 and Menz and Keenan 1997) is described as *"clinically unacceptable"* (Menz and Keenan 1997, p.198). Keenan and Bach (2006) reported that the mean range results for both NCSP and RCSP were inclusive of everted and inverted angles (for example NCSP = -2 (eversion) to 13° (inversion)). This indicates that there is a lack of agreement between assessors in not only the degree of the angle, but the direction of the angle of the bisection line being measured.

Investigation	Method of investigation	Intra-assessor reliability	Inter-assessor reliability
Menz and Keenan (1997)	10 participants 2 assessors Angle finder	r = 0.811 SEM = ±3.77	r = <0.639 SEM = ±6.52
Menz and Keenan (1997)	10 participants 2 assessors Digital goniometer	r = 0.168 SEM = ±8.47	r = <0.561 SEM = ±4.44
Keenan and Bach (2006)	24 participants 4 assessors Plastic goniometer	-	r = 0.335 SD= 2.5° Range = -2° to 13°
Picciano et al (1993)	15 participants 2 assessors Plastic goniometer	ICC = <0.18 SEM = <2.46	ICC = 0.15 SEM = 2.43

Table 2.1 presents the intra and inter-assessor reliability of the examination of the frontal plane angle of the subtalar joint in NCSP. * symptomatic participants

Overall, this amount of inter-assessor variation suggests that it is not possible to achieve the precision demanded by the Root et al (1971, 1977) assessment protocol. Root et al (1977) proposed that as little as one or two degrees can result in the classification of a normal or abnormal foot, but this level of accuracy appears to not be possible with this examination method (Keenan and Bach 2006).

The relationship between the angle of NCSP and the movement of the subtalar joint during walking

In the normal foot, Root et al (1971) proposed that the subtalar joint should be in a neutral (0°) position in NCSP, and will pass through this neutral position just prior to heel lift during midstance. However, McPoil and Cornwall (1994), McPoil and Cornwall (1996a) and Pierrynowski and Smith (1996) report that in asymptomatic feet the frontal plane angle of the calcaneus relative to the tibia is not in a neutral position in NCSP, and the calcaneus is everted relative to the tibia during midstance and at heel lift.

Root et al (1971, 1977) implied that if the subtalar joint is in an inverted or everted angle when examined in NCSP, then the subtalar joint will be everted the same angle just prior to heel lift during midstance. However, McPoil and Cornwall (1994), McPoil and Cornwall (1996a) and Pierrynowski and Smith (1996) incorrectly interpreted the Root et al (1977) description. For example, in McPoil and Cornwall (1996a) they state that "*the path of rearfoot motion did not intersect subtalar joint neutral position for any of the 62 feet studied"* (McPoil and Cornwall 1996a, p.374). Root et al (1977) proposed that the subtalar joint would only intersect its neutral position just prior to heel lift if the subtalar joint was in a neutral (0°) position when examined in NCSP. In McPoil and Cornwall (1994) and McPoil and Cornwall (1996a) the calcaneus was inverted relative to the tibia in NCSP. Therefore, Root et al (1977) would propose as demonstrated by the results of these investigations that the calcaneus will be in an everted position during midstance. To pass through the angle measured in NCSP, the feet measured in McPoil and Cornwall (1994) and McPoil and Cornwall (1996a) would have to invert considerably more than the normal foot during midstance which Root et al (1977) did not propose.

In all of the afore-mentioned investigations the calcaneus was everted relative to the tibia a far greater angle than it is inverted in NCSP, highlighting the limited relationship between these parameters. McPoil and Cornwall (1996a) report an inverted angle of only 1.2° (SD=3.7°) for NCSP, and an everted angle of 6.3° at heel lift. This is similar to the results from McPoil and Cornwall (1994). However, to place the subtalar joint into a neutral position, McPoil and Cornwall (1994) and McPoil and Cornwall (1996a) focused on placing the medial and lateral edges of the talus in congruence with the navicular. They then used the height of the medial longitudinal arch as a surrogate indicator of the subtalar joint was in a neutral position. This is considerably different to the protocol described by Root et al (1977), and therefore the results from these investigations are not a direct critique of the Root et al (1977) description.

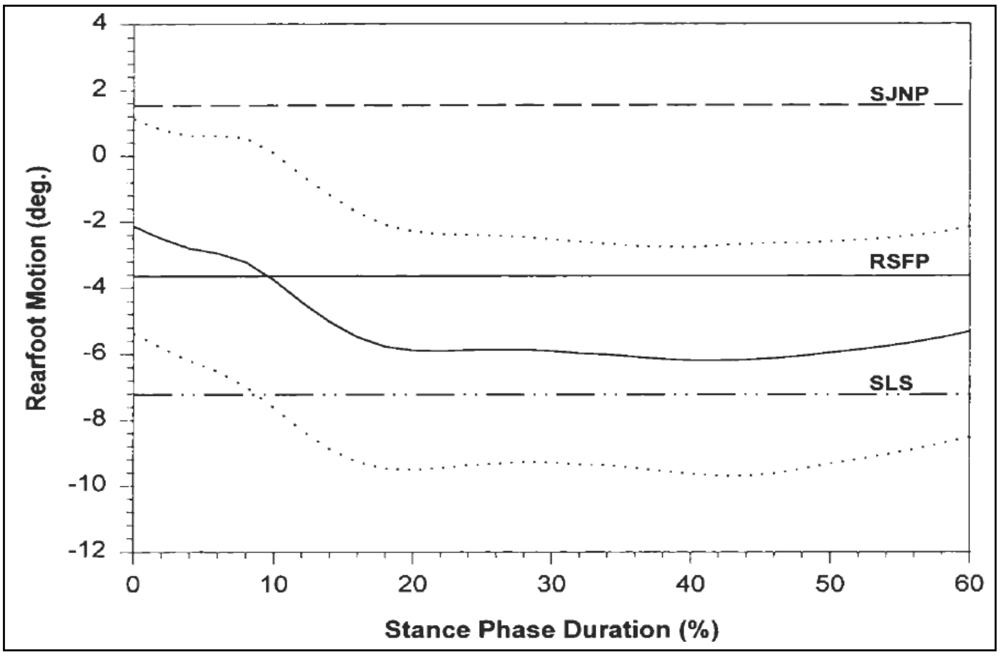


Figure 2.3 is adapted from McPoil and Cornwall (1996a). It presents the frontal plane movement of the calcaneus relative to the tibia (rearfoot motion) during the stance phase of the gait cycle with the frontal plane angle of the calcaneus relative to the tibia measured in RCSP (RSFP), NCSP (SJNP) and single leg stance (SLS). The dashed lines represent the standard deviation of the frontal plane movement of the calcaneus relative to the tibia.

Root et al (1977) classified feet as abnormal if the subtalar joint is not in a neutral (0°) angle when examined in NCSP and that are pronated during midstance. They proposed that these abnormal feet will either be pre-disposed to or present with injury. However, all participants included in McPoil and Cornwall (1994) and McPoil and Cornwall (1996a) were asymptomatic. Although Kitaoka et al (2006), and others investigating foot kinematic in people without symptoms (Cornwall and McPoil 1999a, Leardini et al 2007, Hunt et al 2001a, Jenkyn and Nicol 2007, Simon et al 2006, Lundgren et al 2007) have not measured the angle of the foot in NCSP, they all report that the calcaneus everted relative to the tibia or talus during midstance. Overall, this questions whether Root et al (1977) description of the normal foot is representative of the symptom free foot.

A possible explanation for the large difference in the angle measured by these investigations could be because the measurement technique used. McPoil and Cornwall (1994) and McPoil and Cornwall (1996a) used 2D video analysis which has several limitations (Keenan and Bach 1996). The placement of markers in McPoil and Cornwall (1994) and McPoil and Cornwall (1996a) onto the bisection lines drawn onto the calcaneus and tibia would also be subject to error due to skin and soft tissue movement. For example, a marker was placed onto the tendo-achilles which would undoubtedly move during walking and not be representative of calcaneal movement. Skin movement artefact is described by Karlsson and Tranburg (1999), Angeloni et al (1993) and Leardini et al (2005) as a key source of error in gait analysis. They proposed that marker placement should be selected wisely and avoid areas of large soft tissue displacement and joint margins. This is something Kitaoka et al (2006), and others (Cornwall and McPoil 1999a, Leardini et al 2007, Hunt et al 2001a, Jenkyn and Nicol 2007, Simon et al 2006, Lundgren et al 2007) have taken into consideration.

These investigations (McPoil and Cornwall 1994, McPoil and Cornwall 1996a, Pierrynowski and Smith 1996) have used the movement of the calcaneus in the frontal plane relative to the tibia to represent the movement of the subtalar joint. This is because it is not possible to measure the movement of the talus from the skins surface. Although there are several limitations with this methodology, Root et al (1971, 1977) stated that at the subtalar joint, only the calcaneus will move in the frontal plane when weight bearing. Therefore, this measurement technique seems an appropriate representation of their description.

The Root et al (1971, 1977) classification of the rearfoot as varus or valgus

Root et al (1971, 1977) proposed that if the frontal plane angle of the subtalar joint measured in NCSP is inverted, the foot is classified as a rearfoot varus. If it is everted, the foot is classified as a rearfoot valgus.

Root et al (1977) proposed that to compensate for a rearfoot varus deformity, and maintain plantigrade contact of the foot with the supporting surface the subtalar joint will have to remain in a pronated position when both the heel and forefoot are in contact with ground. Since the subtalar joint is in a pronated position during midstance, Root et al (1977) believed that the foot will be unable to transform into a rigid lever, and it will remain an unstable mobile adaptor. This flexibility would expose the foot to risk of injury and deformity.

Root et al (1977) inferred that the range of subtalar joint compensatory pronation required to compensate for the magnitude of the rearfoot varus deformity is dependent on the range of eversion available at the subtalar joint. This is determined from the non-weight bearing examination of subtalar joint range of motion. A fully compensated rearfoot varus was present if the range of frontal plane motion at the subtalar joint is sufficient to fully compensate for the inverted position of the calcaneus. A partially compensated rearfoot varus was present if the range of subtalar joint frontal plane motion is partially sufficient to compensate for the inverted position of the calcaneus, and the rearfoot will remain in a partially inverted position.

However, more recent investigations (Leardini et al 2007, Cornwall and McPoil 1999a, Moseley et al 1996, Kitaoka et al 2006, Hunt et al 2001a, McPoil and Cornwall 1994, McPoil and Cornwall 1996a) using asymptomatic participants, report that the calcaneus remains in an everted position relative to the tibia, and does not invert or supinate from forefoot loading.

The Root et al (1977) description of the function of a foot classified with a rearfoot valgus is in agreement with the more recent literature discussion of feet classified with a pes valgus, or adult acquired flat foot deformity. Kido et al (2011) and Helliwell et al (2007) stated that feet classified with a valgus foot type as proposed by Root et al (1977) remain in a pronated position during the stance phase of walking. These feet commonly present with injury.

The relationship between RCSP and the movement of the foot during walking

In the normal foot, Root et al (1971) stated that the subtalar joint should be between 2° inverted, to 2° everted in RCSP. Root et al (1971) proposed that the examination of the frontal plane angle of the subtalar joint in RCSP represents the position of the foot during midstance. Therefore, it will demonstrate the range of compensatory pronation, or supination of the subtalar joint required toaccommodate for any structural deformities (e.g forefoot and/or rearfoot varus).

2.4.2 Examination of the range of frontal plane motion at the subtalar joint

The Root et al (1971) examination of the passive non-weight bearing measurement of the range of frontal plane motion at the subtalar joint involves the movement of the calcaneus from its neutral position, to a maximum inverted position and then to a maximum everted position. Root et al (1977) proposed that there should be a 2:1 ratio of the range of motion available at the subtalar joint when assessed non-weight bearing; with 2/3rds inversion, to 1/3rd eversion.

This examination involves placing the subtalar joint into a neutral position, and the posterior aspect of the calcaneus and lower third of the leg are bisected in the frontal plane. The calcaneus is manually moved to a position of maximum inversion. A new bisection line is drawn which extends from half way along the original bisection line drawn when the subtalar joint was in a neutral position. A goniometer is then used to measure the angle between the two bisection lines. The same procedure is repeated when the calcaneus is manually moved to a position of maximum eversion.

The intra- and inter-assessor reliability of the examination of the range of frontal plane motion at the subtalar joint

Many (Elveru et al 1988, Diamond et al 1989, Smith-Oricchio and Harris 1990, Weiner Ogilvie et al 1997, Nigg et al 1992, and Youberg et al 2005) have highlighted the numerous difficulties with the Root et al (1971) examination of the range of frontal plane motion at the subtalar joint, and that it does not demonstrate a 2:1 ratio.

The main source of error as similar to the examination of NCSP and RCSP is related to the drawing of the bisection line onto the posterior aspect of the calcaneus. Therefore, the same problems with soft tissue and skin movement artefact, marker pen thickness, and the questionable validity of using this measurement technique to represent the frontal plane movement of the subtalar joint, are still very apparent here. Weiner Ogilvie et al (1997) reported that the possible contraction of the extrinsic muscles of the foot by the patient when the foot is being manipulated could limit the movement of the calcaneus. Other difficulties include: the variability in the torque applied to the joints, and overall if it is possible to just measure the movement of the subtalar joint using this examination method. Pierrynowski and Smith (1996) and Pierrynowski et al (1997) report that the assessment of the patient in a prone position which Root et al (1971) advocated, produced more consistent and reproducible results. Although when the participant was seated in these investigations, assessors were more accurate at placing the subtalar joint in to a neutral position.

Most investigations (Elveru et al 1988, Diamond et al 1989 and Weiner-Oglivie et al 1997), apart from Smith-Orrichio and Harris (1990) report moderate to very good intra-assessor reliability, but poor to moderate inter-assessor reliability. Elveru et al (1988) indicated that the key source of error in this examination is caused by the difficulty of placing the subtalar joint into a neutral position.) They reported that the intra and inter-assessor reliability of this examination marginally improved when the range of inversion, and eversion were not measured from the neutral position of the subtalar joint. Instead the resting position of the foot was used. Although, the ICC values improved from only ICC = 0.12, to ICC = 0.17 for inter-assessor reliability.

Investigation	Method of investigation	Inversion		Eversion	
		Intra-assessor reliability	Inter-assessor reliability	Intra-assessor reliability	Inter-assessor reliability
Elveru et al (1988)	50 participants* 14 assessors Plastic goniometer	ICC =<0.74	ICC = <0.32	ICC = <0.75	ICC = <0.17
Diamond et al (1989)	31 participants* 2 assessors Plastic goniometer	ICC =<0.96 SEM = 2	ICC = <0.86 SEM = 3	ICC = <0.96 SEM = 1	ICC = 0.79 SEM = 4
Weiner Ogilvie et al (1997)	20 participants 2 assessors Polhemus Isotrack II tracking system	ICC = <0.97	ICC = 0.84	ICC =<0.93	ICC = 0.79
Smith-Oricchio and Harris (1990)	20 participants 2 assessors Plastic goniometer	ICC = 0.42	-	ICC = 0.25	-

Table 2.2 presents the intra- and inter-assessor reliability of the non-weight bearing examination of the range of frontal plane motion at the subtalar joint. * symptomatic participants.

Agreeably, Diamond et al (1989) and Weiner Oglivie et al (1997) did not use the neutral position of the subtalar joint as a starting position and both reported high ICC values for intra-tester reliability, and good to very good ICC values for inter-tester reliability (Table 2.2). However, Diamond et al (1989) and Weiner-Oglivie et al (1997) used only two assessors, while Elveru et al (1988) used fourteen. This may explain the considerable difference in reliability results, and question the clinical use of this examination.

The range of frontal plane motion at the subtalar joint assessed non-weight bearing is not a 2:1 ratio

Youberg et al (2005), Weiner Oglivie et al (1997) and Nigg et al (1992) state that there is not a 2:1 ratio of frontal plane motion at the subtalar joint when it is examined non-weight bearing. Although, none of these investigations have followed the Root et al (1971) examination protocol exactly. Weiner Oglivie et al (1997) reported that the mean range of eversion measured by one assessor was 39.6% (SD=11.8%), and the second assessor reported a mean of 52.1% (SD = 17.2%) of eversion. Even though the range of inversion is not provided, the percentage of eversion measured means overall it cannot represent a 2:1 ratio of motion.

Youberg et al (2005) used a semi-static examination method and measured 30.5° (SD=6.8°) inversion, to 9.0° (SD=3.5°) eversion. Using a similar design, Nigg et al (1992) measured the movement of the calcaneus in response to manual external and internal rotation of the tibia. They reported a smaller range of inversion with 20.61° (SD=6.7°), and a greater range of eversion with 14.93° (SD=5.1°).

Root et al (1977) proposed that the range of frontal plane motion at the subtalar joint measured in a non-weight bearing examination, will determine the functional ability of the subtalar joint to compensate for any structural deformities of the rearfoot. Root et al (1977) referred to Wright et al (1964) and stated that in the normal foot the subtalar joint should invert between 4-6°, and evert between 4-6°. This is more similar to 1:1 ratio. However, Close et al (1965), who is referenced by Root et al (1977), measured the range of frontal plane motion at the subtalar joint with intra-cortical bone pins. They reported considerable inter-subject variation in the frontal plane movement of the subtalar joint. The range of motion varied between 9.93° to 28.00° from the eight participants tested. Although, in contrast Nester et al (2006) and Lundgren et al (2007) measured the range of frontal plane motion at the subtalar joint during walking with intra-cortical bone pins. They reported a mean range of 9.8° (SD=1.8°) (Lundgren et al 2007) and 9.7° (SD=5.2°) (Nester et al 2006). This is still a smaller range of motion than Root et al (1977) proposed and less inter-participant variation than Close et al (1965).

2.4.3 Examination of the range of dorsiflexion at the ankle joint

Root et al (1971, 1977) proposed that the range of dorsiflexion measured at the ankle joint in a static examination will predict the sagittal plane angle of the ankle joint at heel lift. To measure the range of dorsiflexion at the ankle joint in a non-weight bearing examination, Root et al (1971) described how one arm of a goniometer is placed along the lateral plantar aspect of the foot, and the other arm is placed along a bisection line that is drawn onto the lower lateral third of the leg, extending from the centre of the lateral malleolus. With the subtalar joint placed in a neutral position, Root et al (1971) stated that the foot is manually dorsiflexed onto the leg. Root et al (1977) proposed that placing the subtalar joint into a neutral position is essential to isolate the sagittal plane motion of the ankle joint. If the subtalar joint is allowed to pronate, Root et al (1977) stated that this will increase the range of dorsiflexion measured because dorsiflexion is a component of open chain (non-weight bearing) pronation of the subtalar joint.

The intra- and inter-assessor reliability of the examination of the range of dorsiflexion at the ankle joint

Moseley and Adams (1991), Elveru et al (1988) and Rome (1996) describe how there are numerous difficulties with the static non-weight bearing examination of the range of dorsiflexion at the ankle joint. These include: the poor identification of bony landmarks, variation in the force or torque applied by the examiner when moving the foot onto the leg, inadvertent muscular contraction from the patient, and the difficulty in reading the measurement recorded on a device.

Investigation	Method of investigation	Intra-assessor reliability	Inter-assessor reliability
Elveru et al (1988)	50 participants* 14 assessors Plastic goniometer	ICC = 0.91	ICC = 0.50 Same position ICC = 0.40 Different position ICC = 0.59
Diamond et al (1989)	31 participants* 2 assessors Plastic goniometer	ICC = <0.96 SEM = 1	ICC = <0.87 SEM = 2
Jonson and Gross (1995)	18 participants 2 assessors Plastic goniometer	ICC = 0.74 SD = 1.32°	ICC = 0.65 SD = 2.04°
Menz et al (2003)	31 participants** 3 assessors Modified lunge examination Plastic goniometer	-	ICC = 0.87
Moseley and Adams (1991)	15 participants* 5 assessors Lidcombe template	ICC = 0.97	-
Konor et al (2012)	20 participants 1 assessor Weight bearing lunge examination Plastic goniometer	ICC = <0.96 SEM = 1.8	-

Table 2.3 presents the intra- and inter-assessor reliability of the non-weight bearing examination of the range of dorsiflexion at the ankle joint. *asymptomatic and symptomatic participants. ** older patients (age range = 76-87years).

Elveru et al (1988) and Jonson and Gross (1997) report good to very good intra and inter-assessor reliability results with ICC = 0.90 (Elveru et al 1988) and Jonson and Gross (1997) reportICC = 0.74. For inter-assessor reliability, they reported moderate to good ICC values with ICC = 0.50 (Elveru et al 1988) and ICC= 0.65 (Jonson and Gross (1997). The reliability results from these investigations may be inadvertently higher, because the subtalar joint was not placed into a neutral position first. Elveru et al (1988) reported that the examination of the range of frontal plane motion at the subtalar joint was not as reliable if the subtalar joint was positioned in a neutral position first. Therefore, these results may not reflect the reliability of the measurements obtained from following the Root et al (1977) protocol. Some have proposed that using a specifically designed apparatus (Moseley and Adams 1991) or assessing the patient weight bearing (Konor et al 2012) is a more reliable method of examination. Moseley and Adams (1991) advocate the use of a lidcombe template apparatus as it helps to standardise the amount of joint torque applied. Agreeably, this appears to improve the reliability as they reported ICC values of ICC = 0.97.

The assessment of the patient weight bearing using a standing lunge technique is described by Konor et al (2012) as more reliable than a non-weight bearing examination. Konor et al (2012) reported ICC values of 0.96 and smaller SEM values than the non-weight bearing examination too, with SEM= 1.8 to 2.8. However, Konor et al (2012) reported only intra-assessor reliability. To try and determine the clinical value of this examination, inter-assessor reliability results are required as it is highly unlikely that the same clinician will always assess the same patients. However, even with the good to excellent reliability between assessors, there is still variation in the measurements obtained, which undermines their clinical value. Keenan (1997) and Moseley and Adams (1991) emphasised that because a foot can be classified as abnormal from as little as 1° from the proposed normal value, perfect reliability between assessors is required. The minimal detectable change, which is the minimal amount of change incurred outside of the error incurred, is reported by Moseley and Adams (1991) to be up to 7.7°. This large variation would not satisfy the precision required by the Root et al (1977) protocol and it would affect the classification of the foot and the treatment rationale used.

The relationship between the range of dorsiflexion at the ankle joint measured in a non-weight bearing examination and the movement of the ankle joint during walking.

Root et al (1971, 1977) proposed that the minimum range of dorsiflexion to be measured in the static examination of the ankle joint is 10°. This is so that the ankle joint can be dorsiflexed to this angle at heel lift. If the range of dorsiflexion measured in a static examination is less than 10°, Root et al (1977) classified this as ankle equines deformity. They assumed the ankle joint will be unable to dorsiflex to 10° at heel lift and that the heel will lift from the ground earlier than normal. To compensate for this limitation in the range of motion, they proposed that the subtalar joint will abnormally pronate during midstance, preventing the foot from transforming into a rigid lever and resulting in injury.

However, many (Leardini et al 2007, Arndt et al 2004, Lundrgen et al 2007, Hunt et al 2001a, Simon et al 2006, Nester et al 2006, Kitaoka et al 2006, and Moseley et al 1996) have reported that the calcaneus or talus is not dorsiflexed relative to the tibia up to or more than 10° at heel lift. All of these investigations also report that the calcaneus everted relative to the talus or tibia during midstance, to indicate pronation of the subtalar joint. Root et al (1977) would classify these feet as abnormal, which will present with or be pre-disposed to injury, except all participants included in these investigations are asymptomatic. This strongly indicates that feet do not require 10° of dorsiflexion to be symptom free and pronation of the subtalar joint is a normal movement of the foot and not a cause of injury. Cornwall and McPoil (1999b) reported that contrary to Root et al (1977), feet classified with less than 10° range of dorsiflexion at the ankle joint from static examination; do not pronate more at the subtalar joint during walking. In feet classified with less than 10°, the peak angle of calcaneal eversion relative to the tibia was only -0.2° ($p=>0.05$) greater than feet classified more than 15° of ankle dorsiflexion. The time to this peak angle of eversion was only 5.4% ($p=>0.05$) earlier than feet classified with more than 15° (Cornwall and McPoil 1999b). However, Cornwall and McPoil (1999b) describe how the time to heel lift was 2.8% earlier ($p=<0.05$), and the time to re-inversion was 6.29% (p=<0.05) earlier in feet classified with less than 10° from static examination. This could be construed to be in part agreement with what Root et al (1977) proposed.

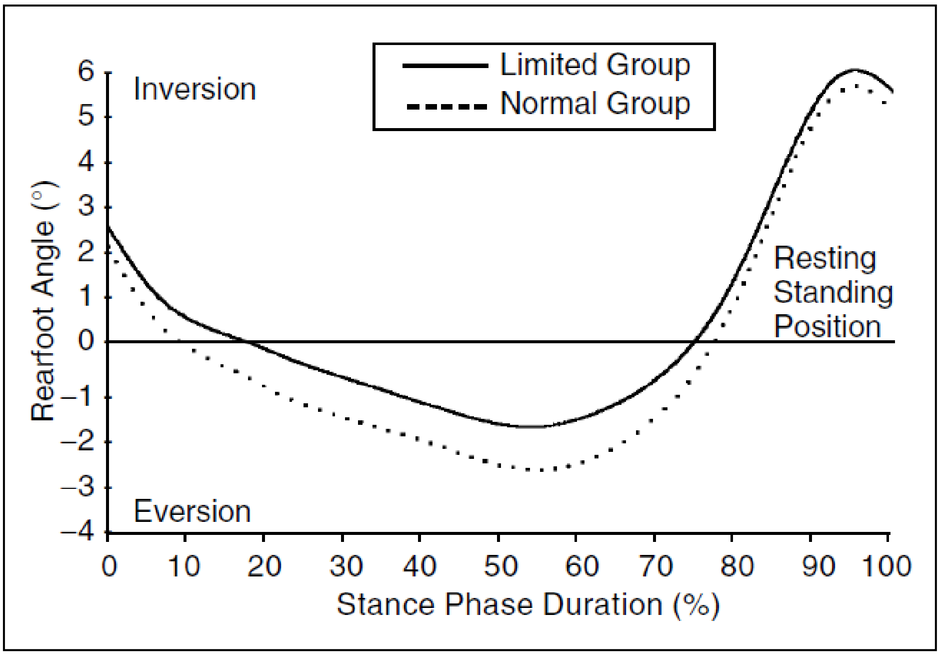


Figure 2.4 presents the frontal plane movement of the calcaneus relative to the tibia (rearfoot) during the stance phase of the gait cycle in feet classified with a limited (<10°) or normal (>15°) range of dorsiflexion at the ankle joint measured from static examination (Cornwall and McPoil 1999b).

Overall, it is unclear as to whether the range of dorsiflexion at the ankle joint measured from static examination can be used to predict the sagittal plane movement of the ankle joint during the stance phase of the gait cycle (Charles et al 2010). DiGiovanni et al (2002) proposed in support of Root et al (1977) that more feet were diagnosed with a musculoskeletal injury if the range of dorsiflexion at the ankle joint from a static examination was less than 10°. However, the participants used by DiGiovanni et al (2002) were all retired ex-military servicemen. In consideration of the high prevalence of injury in military personnel, it may suggest that these results are not indicative of the general population. In contrast, Orenduff et al (2006) suggested that feet classified with less than 5° of dorsiflexion at the ankle joint from a static examination should be classified as an ankle equinus. This idea was based on the observation that the plantar pressure under the forefoot was significantly greater during the stance phase of walking in those classified with less than 5°. However, all participants included by Orenduff et al (2006) were diagnosed with diabetes and other factors may have caused the increase in plantar pressure, such as changes in plantar tissue.

2.4.4 Examination of the forefoot to rearfoot relationship

Root et al (1971, 1977) proposed that the examination of the forefoot to rearfoot relationship can be used to examine the forefoot and midtarsal joint. Firstly, to identify if there is a structural deformity of the forefoot in the frontal plane, and second, to measure the range of motion available at the midtarsal joint. Root et al (1971, 1977) described how the midtarsal joint is the mechanism joining the rearfoot and forefoot, with the position and motion of the former affecting the latter.

To conduct the examination of the forefoot to rearfoot relationship as described by Root et al (1977), the patient is in a prone position, and the subtalar joint is held in a neutral position. Pressure is applied to the fifth metatarsal to pronate the midtarsal joint around both axes, locking the forefoot against the rearfoot. The angulation of the forefoot relative to the rearfoot is then measured by placing a measuring device or goniometer on the plantar aspect of the forefoot. Root et al (1971) advocated the measurement of the whole forefoot inclusive of the first to the fifth metatarsal heads to measure the angle of the forefoot. Although, Root et al (1971) suggested that if the first or fifth metatarsals are not in the same plantar plane as the second to fourth metatarsals, most commonly because of a deformity of the first ray (e.g dorsiflexed or plantarflexed), then the plantar plane of the second to fourth metatarsals should be used.

Root et al (1971) stated that conducting the examination of the forefoot to rearfoot relationship can be difficult and practical experience is required. Some of the difficulties highlighted by Root et al (1971) and more recent literature (Garbalosa et al 1994, Evans et al 2003, Diamond et al 1989, McPoil et al 1988, Buchanan and Davis 2005) include: the difficulty of maintaining the subtalar joint in a neutral position whilst holding the fifth metatarsal, and using the goniometer, or forefoot measuring device to take the a measurement. Evans et al (2003) and Buchanan and Davis (2005) described how contraction of the tibialis anterior by the patient when the examination is conducted will create an inverted forefoot, representative of a structural deformity of the foot. They (Evans et al 2003 and Buchanan and Davis 2005) also emphasised how the variation between assessors in how much pressure is applied to the fifth metatarsal can also significantly affect the position of the forefoot. Other difficulties of this examination appear to be generic sources of error for the majority of the biomechanical examinations of the foot described by Root et al (1971, 1977). These include the low reliability of placing the subtalar joint into a neutral position, and the use of the bisection line drawn onto the posterior aspect of the calcaneus to represent the frontal plane position of the subtalar joint.

The intra- and inter-assessor reliability of the examination of the forefoot to rearfoot relationship

Aside from these difficulties, Evans et al (2003), Diamond et al (1989) and

Garbalosa et al (1994) all report good to excellent intra- and inter-assessor reliability when using both a goniometer, and or forefoot measuring device. Garbalosa et al (1994) reported very good agreement between assessors using a goniometer (r = >0.894), or a forefoot measuring device (r = >0.929), the latter is what Root et al (1971) advocated. Evans et al (2003) reported ICC values of ICC = 0.823 for intra-, and ICC = 0.70 for inter-assessor reliability when examining the forefoot to rearfoot relationship in adults. In contrast, the ICC values calculated by Evans et al (2003) for children (ICC = 0.28), and adolescents (ICC =0.53) indicate poor to moderate reliability. In agreement with Lorimer et al (2007), this suggests that children's feet are more difficult to examine, possibly due to the difficulty in maintaining the foot position when the measurement is being taken, and the small size of the feet. Although the reliability indices indicate good reliability, Evans et al (2003) highlighted howthe SEM values (SEM = 2.1 (adult)) are large considering the small mean result (2.01°). Diamond et al (2003) reported a similar result with ICC values of ICC = <0.93 for intra, and ICC = <0.77 for inter-assessor reliability. However, the mean angle of the forefoot to rearfoot relationship measured by Diamond et al (1989)was in a varus direction, but the large mean standard deviation values of SD =3° suggest there is large variation in the measurements between assessors.

The Root et al (1971, 1977) classification of the forefoot as varus or valgus

Root et al (1971, 1977) referring to Hlvac (1970) and Steindler (1929) described how a foot is classified with a forefoot varus if the forefoot is inverted, or a forefoot valgus if the forefoot is everted relative to the rearfoot. They proposed that to compensate for these deformities, the subtalar joint will abnormally pronate during the gait cycle. Root et al (1977) stated that the close relationship between the subtalar and midtarsal joints allowed the subtalar joint to control the movement of the forefoot and restore a plantigrade contact of the foot with the floor.

In a foot classified with a forefoot valgus, the subtalar joint will remain in a pronated position during propulsion. In a foot classified with a forefoot varus, the subtalar joint will remain in a pronated position throughout the gait cycle. As the subtalar joint is in a pronated position, when it should be supinating, Root et al (1977) stated that the foot will be unable to transform into a rigid lever during midstance or propulsion. This will cause injury and deformity to the soft tissue and bony structures of the foot, in particular to the first metatarsophalangeal joint.

In agreement with Root et al (1977), Donatelli et al (1999) reported that in feet classified with a forefoot varus the calcaneus everted relative to the tibia during the contact, midstance and propulsion phases of the gait cycle. However, the cohort used by Donatelli et al (1999) included non-injured and injured professional baseball players and the frontal plane angle of the forefoot to rearfoot relationship was only 0.1° ($p = >0.05$) greater in the non-injured than the injured players. This suggests that this assessment provides little inference about the symptomology of the patient.

Furthermore, some (Garbalosa et al 1994, Buchanan and Davis 2005, McPoil et al 1988) have demonstrated that a large percentage of asymptomatic individuals can also be classified with a forefoot varus, or valgus. For example, McPoil et al (1988) classified from a cohort of 58 asymptomatic feet 44.8% with a forefoot valgus, and 8.62% with a forefoot varus. In contrast, Buchanan and Davis (2005) classified 92% of feet (n=43/51), and Garbalosa et al (1994) classified 86.6% (n=208/240) of feet with a forefoot varus. Both using large cohorts of participants. Although, McPoil et al (1988) and Garbalosa et al (1994) followed the Root et al (1977) protocol and classified feet as a forefoot varus or valgus if the frontal plane angle of the forefoot was inverted or everted from 0°. Buchanan and Davis (2005) classified feet as a forefoot varus if the forefoot was inverted more than 8° from 0°. Feet classified with an inverted angle of between 1°-8° were classified as “neutral,” although Buchanan and Davis (2005) included them within the forefoot varus classification. Less than 1° inverted was classified as a forefoot valgus. There is a dearth of literature describing the kinematics of the foot in feet classified with a forefoot varus, or forefoot valgus. Results from the afore-mentioned investigations (Buchanan and Davis 2005, McPoil et al 1988, Garbalosa et al 1994, Donatelli et al 1999), strongly indicate that further investigation is required into understand the biomechanical function of feet classified with this type of structural deformity. It will then be possible to determine if the examination of the forefoot to rearfoot relationship is a useful predictor of injury.

2.4.5 Examination of the sagittal plane position and mobility of the first ray

Root et al (1971, 1977) proposed that the examination of the first ray involves the examination of its position and mobility. This aims to determine if there is structural deformity of the first ray, and it should provide an indication as to whether it is congenital or an acquired deformity. The protocol for the examination of the first ray described by Root et al (1977) firstly involves placing the subtalar joint into a neutral position. This is described by them as imperative, as pronation of the subtalar joint will increase the range of motion at the first ray, and supination of the subtalar joint will decrease the range of motion at the first ray. Root et al (1971) described how one hand should stabilise the lesser metatarsals and the other hand will hold the first metatarsal. In this position, Root et al (1971) stated that the clinician should classify the position of the first ray as neutral, plantarflexed (below plantar plane of lesser metatarsals), or dorsiflexed (above plantar plane of lesser metatarsals). To assess the range of motion, Root et al (1971) described how the clinician should maximally dorsiflex the first ray, and then maximally plantarflex the first ray.

Root et al (1971) hypothesised that the first ray is classified as a plantarflexed deformity if the range of plantarflexion exceeds the range of dorsiflexion. There are two classifications of a plantarflexed first ray: a congenital plantarflexed first ray where there is no limitation in the range of motion of the first ray; or an acquired plantarflexed first ray where there is restriction in the range of motion. It is classified as a dorsiflexed deformity if the range of dorsiflexion exceeds the range of plantarflexion. Root et al (1971) provides no numerical parameters as to what constitutes the normal range of first ray motion other than these parameters. There few investigations (Hamill et al 1989, McPoil et al 1988) reportinhg the incidence or movement of feet classified with a deformity of the first ray followed the Root et al (1977) protocol.

In contrast, there are many investigations (Glascoe et al 2005, Cornwall et al 2004, Glascoe et al 1999, Glascoe et al 2000, Allen et al 2004, Lee and Young 2001) that have described just the examination of the range of dorsal mobility of the first ray. This can be through using either a clinical based examination, or a specifically designed load cell device. This measurement has received considerable attention within the literature due to the proposed relationship between an excessive range of dorsal mobility, and the development of hallux abducto-valgus (Lee and Young 2001). Although very few (Allen et al 2004), relate this measurement to the movement of the first ray or the foot during walking.

The intra- and inter-assessor reliability of the examination of the sagittal plane position and mobility of the first ray

There are very few investigations that have reported the intra- or inter-assessor reliability examination of the first ray following the Root et al (1971) examination protocol. Hamill et al (1989) reported good to very good correlation values between the measurements from test and re-test for the total range of motion at the first ray (r = 0.77), the range of plantarflexion (r = 0.73), and dorsiflexion (r = 0.85). Although this is only a reflection of intra-assessor reliability, the movement of the first ray into plantarflexion and dorsiflexion is likely to be more consistent. For the range of dorsal mobility of the first ray, the intra and inter-assessor reliability is described as poor to moderate. Glascoe et al (2005) reported very low ICC values with ICC = 0.06 for intra, and ICC = 0.05 for inter-assessor reliability, when using a ruler to measure the range of dorsal mobility. The large inter-assessor variation is further highlighted by the large mean SEM values of <1.2mm. These are comparatively large considering the mean value is only <5.3mm. A similar level of lack of agreement between assessors was reported by Cornwall et al (2004), with only a 30% agreement for the classification of the quality (hypo/hypermobility or neutral) of the range of dorsal mobility at the first ray. The lack of agreement between assessors is further highlighted by the individual levels of agreement for each classification of the first ray. For the classification of a hypomobile first ray there was a 12.5% agreement, 34.1% agreement for classification of a neutral first ray, and 25.0% agreement for classification of a hypermobile first ray.

Experienced clinicians who participated in Cornwall et al (2004) and Glascoe et al (2005) should be able to consistently classify or measure hyper and hypo mobility. Especially as one infers rigidity, and the other excessive movement. However, Lee and Young (2001) suggest that a cause of this poor reliability for this measure could be that there is very little quantifiable evidence of what constitutes hypo, or hyper mobility of the first ray. Glascoe et al (2005) and Cornwall et al (2004) also reported that some clinicians had considerable difficulties in trying to maintain the foot in the required position, and that it was difficult to ascertain precise measurements, due to the cumbersome design of the method of examination.

In an attempt to provide an accurate quantification of the range of dorsal mobility of the first ray, Glascoe et al (2005) and Cornwall et al (2004) assessed the same patients with a specifically designed load cell device. This was developed by Glascoe et al (2005) To standardise the amount of load applied to the first ray for each participant. The ICC values for the load cell device indicate almost perfect reliability (ICC = 0.98, Glascoe et al 2005). However, this type of equipment is rarely suitable for the confines of clinical practice. Overall, this indicates that the examination of the range of dorsal mobility of the first ray does not offer a more reliable examination than the Root et al (1971, 1977) protocol.

The Root et al (1971, 1977) classification of a structural deformity of the first ray

Root et al (1977) proposed that a foot classified with a plantarflexed first ray deformity will compensate for this structural deformity when the forefoot is in contact with the ground. Root et al (1977) stated that the subtalar joint will demonstrate abnormal pronation and supination of the midtarsal joint during propulsion. This, they proposed, will invert the forefoot from its everted position, restoring plantigrade contact of the forefoot with the supporting surface. Pronation of the subtalar joint and supination of the midtarsal joint during midstance and propulsion is described by Root et al (1977) as abnormal because in the normal foot the subtalar joint supinates during those phases. They describe how the inability of the foot to act as a rigid lever will create skeletal flexibility within the foot. This will result in abnormal shearing forces, subluxations of joints, and development of callus on the overlaying skin of the forefoot.

Hamill et al (1989) reported that in feet classified with a plantarflexed first ray there is a significant decrease in the range of internal rotation of the tibia during propulsion. As Root et al (1977) hypothesised that internal rotation of the tibia occurs with pronation of the subtalar joint, it would suggest that feet classified with a plantarflexed first ray are not more pronated during this phase.

Root et al (1977) hypothesised that a foot classified with a dorsiflexed first ray will not be able to dorsiflex more than 30° during propulsion. This is because the first metatarsal cannot plantarflex sufficiently enough for it to be in a plantar plane with the forefoot, so the first metatarsophalangeal joint is prevented from being able to dorsiflex to at least 65°. Roukis et al (1996) reported in agreement with Root et al (1977) that the range of dorsiflexion at the first metatarsophalangeal joint significantly decreased when the first ray was placed in a more dorsiflexed position. With the first ray in a neutral position, Roukis et al (1996) stated that the passive range of dorsiflexion at the first metatarsophalangeal joint was 22.7° (SEM=0.4). This decreased to 18.4° (SEM =0.5) with the first ray dorsiflexed 4mm, and decreased further to 14.8° (SEM =0.6) with the first ray dorsiflexed 8mm. Roukis et al (1996) hypothesised that a dorsiflexed position of the first ray will create abnormal compression forces between the base of the proximal phalanx of the hallux, and the base of the first metatarsal. This will prevent it from plantarflexing sufficiently, which will decrease the range of dorsiflexion at the first metatarsophalangeal joint. Root et al (1977) stated that a foot with a limited range of dorsiflexion at the first metatarsophalangeal joint will not be able to function as an efficient rigid lever. It will instead use the lesser metatarsals during propulsion, rather the medial aspect of the forefoot. Agreeably, Cornwall et al (2006) reported a considerable increase in the plantar pressure under the second metatarsal in feet classified with a hypomobile first ray, than feet classified with a hypermobile first ray, This could be indicative of the functional response by the foot to offload onto the lesser metatarsals when there is limited range of motion on the medial aspect of the foot.

Allen et al (2004) suggested that the range of dorsal mobility can be used to infer the movement of the foot during the gait cycle. They reported that in feet classified with a greater range of dorsal mobility of the first ray, the calcaneus was more everted relative to the tibia, and the midfoot was more inverted relative to the calcaneus. However, all participants included in Allen et al (2004) are asymptomatic. This indicates that the difference in the frontal plane movement of the calcaneus and midfoot is as a result of inter-participant variation, rather than a cause of injury. Although, Allen et al (2004) used only three participants per classification of a “lax” (flexible), or a “stiff” (rigid) first ray. Agreeably, a problem with small cohorts is that they can infer that there are larger differences between individuals, when in a larger cohort this would more probably be described as a spectrum of variation (Field 2009). Leardini et al (2007) and others (Lundgren et al 2007, Simon et al 2006, DeMits et al 2012, and Hunt et al 2001)) reported that there is large variation in how the joints of the foot move. This suggests that the results from Allen et al (2004) small samples cannot be used to indicate a difference between these foot types. Instead, further testing with larger cohorts is required.

2.4.6 Examination of the range of dorsiflexion at the first metatarsophalangeal joint

Root et al (1977) proposed that in the non-weight bearing static examination of the first metatarsophalangeal joint, the range of dorsiflexion should be at least 65°. Similarly, at toe off the first metatarsophalangeal joint must be dorsiflexed to 65°. Root et al (1977) primary source is Joseph (1954), who used lateral radiographs to measure the position of the first metatarsophalangeal joint. Joseph (1954) reported that the mean range of dorsiflexion measured from 50 asymptomatic men (left and right feet tested) in a non-weight bearing static examination was 70°. However, Joseph (1954) suggested that the large inter-participant variation reported for all measurements of the first metatarsophalangeal joint, inclusive of non weight bearing, and weight bearing examinations indicates it is unwise to stipulate a specific value to represent the normal foot. Root et al (1977) failed to recognise the importance of this and, as per other examinations of the foot, stated that the normal foot should be classified on a specific value.

There is no description of the examination of the first metatarsophalangeal joint in Root et al (1971). In Root et al (1977) there is a brief description of the examination technique except the description is largely based on the weight bearing examination of the passive range of dorsiflexion. However, because in this position the first metatarsal is prevented from plantarflexing, Root et al (1977) inferred that with heel lift and plantarflexion of the first metatarsal, 65° of dorsiflexion will be possible.

Halstead and Redmond (2006), Hopson et al (1995), Munteanu and Bassed (2006) and Buell et al (1988) emphasised that due to the functional importance of the first metatarsophalangeal joint, there is a definite need for a reliable and accurate clinically based examination. Most investigations have used the static non-weight bearing examination of the range of dorsiflexion at the first metatarsophalangeal joint. However, some (Munteanu and Bassed 2006, Roukis et al 1996, Halstead and Redmond 2006, Nawoczenski et al 1999, Hopson et al 1995, Harradine and Bevan 2000) have suggested different methods to see if they provide a better representation of the movement of this joint during walking. These new methods include: the passive dorsiflexion of the hallux relative to the plantar plane of the foot with the patient weight bearing in RCSP as used in Munteanu and Bassed (2006), Roukis et al (1996), and Halstead and Redmond (2006). The "heel rise" test, the patient is weight bearing in RCSP and is instructed to maintain the hallux in contact with the ground, and lift the heel from the ground of the same foot (Nawoczenski et al 1999, Hopson et al 1995, Harradine and Bevan 2000). Alternatively, active dorsiflexion the first metatarsophalangeal joint by the patient in a non-weight bearing examination has also been employed (Nawoczenski et al 1999, Hopson et al 1995).

The intra- and inter-assessor reliability of the examination of the range of sagittal plane motion at the first metatarsophalangeal joint

Jones and Curran (2012) described how there are many factors than can affect the reliability and accuracy of the static non-weight bearing examination of the range of dorsiflexion at the first metatarsophalangeal joint. These include: the small anatomical size of the joint, incorrect position of the joint, poor identification of bony landmarks, skin and soft tissue movement artefact, incorrect application of and difficulty reading the measuring device.

Intra- and inter-assessor reliability was reported by Munteanu and Bassed (2006), Jones and Curran (2012), and Hopson et al (1995) as good to excellent, but they have not followed the protocol described by Root et al (1971). The results from the latter two investigations are also largely inconclusive, due to limitations in their experimental design. Munteanu and Bassed (2006) measured the range of dorsiflexion at the first metatarsophalangeal joint in RCSP and reported ICC values of ICC =<0.90 for intra-, and ICC = <0.89 for inter-assessor reliability, thus indicating good consistency between the assessors. Hopson et al (1995) reported only intra-assessor reliability, but the results indicate excellent reliability with ICC values of ICC = 0.951 for the static non-weight bearing examination of the range of dorsiflexion. For the step length test, which aims to simulate the position of this joint at toe off, ICC = 0.976 (Hopson et al 1995).

Curran and Jones (2012) reported similarly high ICC values of ICC = <0.975 for intra and ICC = <0.951 for inter- assessor reliability for the examination of the range of dorsiflexion at the first metatarsophalangeal joint. However, the measurements obtained in Curran and Jones (2012) were from a photograph which agreeably makes it much easier to measure a joint angle. This is because it eliminates curvature of the foot, and the joint is already positioned in the relevant position. This method may eliminate two key sources of error associated with this examination, but it also questions the clinical use of it and the validity of this technique is not presented. . Curran and Jones (2012) also reported that for visually estimating the range of dorsiflexion from the same photographs the intra- and inter-assessor reliability ICC values were much more varied. The ICC values ranged from as high as ICC = 0.794, to as low as ICC = 0.167 for inter-assessor reliability.

The relationship between the range of sagittal plane motion at the first metatarsophalangeal joint and the movement of this joint during walking

Root et al (1977) provided no literature evidence to support their description of the movement of the first metatarsophalangeal joint during the gait cycle. Therefore, there is no valid data or explanation to why the first metatarsophalangeal joint must dorsiflex to 65° at toe off, or that the static examination of this joint will predict its movement during walking. This suggests that as with other joints within the midfoot and forefoot, their description is based on hypothesised ideas that are not supported by more recent literature.

Some (Halstead and Redmond 2006, Nawoczenski et al 1999, and Hopson et al 1995) have reported that there are large differences, and only moderate agreement between the static non-weight bearing examination of the range of dorsiflexion at the first metatarsophalangeal joint and the peak angle of dorsiflexion of this joint during propulsion. Halstead and Redmond (2006) reported a mean range of 55.0° (SD=10.7°) dorsiflexion for the non-weight bearing examination of the first metatarsophalangeal joint. In contrast, they measured a mean of only 36.9° (SD=7.9°) for the peak angle of dorsiflexion during propulsion, and report very low and non-significant pearson correlation (r) values of $r = 0.186$ ($p = 0.325$) between these measurements. Hopson et al (1995) measured a greater range of dorsiflexion for the same measurements conducted by Halstead and Redmond (2006), but there was a similar difference between the static and dynamic measurements. For the static non-weight bearing examination, Hopson et al (1995) measured a mean range of 95.9° dorsiflexion, and for the angle at toe off a mean of 64.5° (SD=8.5°). Both values are in agreement with Root et al (1977) stipulated normal range of dorsiflexion at the first metatarsophalangeal joint.

Investigation	Method of investigation	Passive range of dorsiflexion measured in a non-weight bearing static examination	Passive range of dorsiflexion measured in a weight bearing static examination	Range of dorsiflexion measured using the "heel rise test"	Peak angle of dorsiflexion during propulsion/ Angle of dorsiflexion at toe off.
Root et al (1977)	Literature Review	65+°	20-30°	-	65+°
Joseph (1954)	50 participants Radiographic measurement	Mean = 75° Range = 40°-100°	-	-	-
Halstead and Redmond (2006)	15 participants Fastrak EMT system	Mean = 55.0° SD = 10.7°	Mean = 39.4° SD=6.1°	-	Mean = 36.9° SD = 7.9°
Munteanu and Bassed (2006)	33 participants Plastic goniometer	-	Mean = 84.7° SD = 8°	-	-
Nawoczenski et al (1999)	33 participants Electromagnetic tracking device	Mean = 57° SEM = 3.1	Mean = 37° SEM = 2.8	Mean = 58° SEM = 3.2	Mean = 42° SEM =2.3
Hopson et al (1995)	20 participants Plastic goniometer 2D Video (for dynamic measurement)	Mean = 95.9° SD = 9.7°	-	Mean = 109.6 SD = 11.1°	Mean = 64.5° SD = 8.5°
Roukis et al (1996)	10 participants (20 feet assessed) Plastic goniometer	-	Mean = 20.7° SD = 0.4°	-	-
Harradine and Bevan (2000)	26 participants Digital goniometer Measurement conducted in-shoe	-	-	Mean = 85.91° SD= 15.35°	-

Table 2.4 describes the range and angle of dorsiflexion measured at the first metatarsophalangeal joint using three different static based examination methods and during propulsion

In contrast, Nawoczenski et al (1999) reported r values of r = 0.67 (p = <0.001) for a correlation of the same parameters as Hopson et al (1995) and Halstead and Redmond (2006). The measurements were much smaller than the proposed normal range by Root et al (1977). Nawoczenski et al (1999) reported a mean of 57.0° (SEM = 3.1) for the non-weight bearing examination, and 42.0° (SEM= 2.3) for the angle at toe off. Nawoczenski et al (1999) suggested that the weight bearing examinations are better at predicting the movement of the first metatarsophalangeal joint during walking, with r values of r =<0.87 (p = <0.001). However, Nawoczenski et al (1999) stated that there is still up to 16° difference between the static measurements, and the peak angle of dorsiflexion during propulsion. Therefore, the measurements from either examination cannot be used to predict the angle of this joint during walking.

Root et al (1977) stated that if the first metatarsophalangeal joint is unable to dorsiflex to 65° in a static examination, and/or during propulsion it is classified as abnormal. However, investigations (Halstead and Redmond 2006, Nawoczenski et al 1999, Hopson et al 1995, Halstead et al 2005, Munteanu and Bassed 2006, Roukis et al 1996, Harradine and Bevan 2000) described in this section, and others (Carson et al 2001, Simon et al 2006) that have used asymptomatic participants have all reported that the first metatarsophalangeal joint is dorsiflexed to less than 65° during propulsion, or at toe off.

The relationship between the range dorsiflexion at the first metatarsophalangeal joint during walking and abnormal pronation

Root et al (1977) proposed that the main cause of a limitation in the range of dorsiflexion at the first metatarsophalangeal joint during walking is from abnormal pronation of the subtalar joint. Pronation of the subtalar joint was thought to increase the plantar load applied onto the first ray, dorsiflexing the first ray. This would prevent the required plantarflexion from occurring and the first metatarsophalangeal joint will be unable to dorsiflex to 65°. This limitation of motion has been termed a functional hallux limitus.

In agreement with Root et al (1977), Harradine and Bevan (2000) reported that there was a considerable decrease in the range of dorsiflexion at the first metatarsophalangeal joint when the rearfoot was placed in a more everted position. Harradine and Bevan (2000) measured the sagittal plane angle of the first metatarsophalangeal joint in an examination which aimed to simulate the position of the foot at toe off with different degrees of wedges placed under the lateral aspect of the heel. This aimed to increase the everted position of the rearfoot, therefore representing pronation of the subtalar joint. Harradine and Bevan (2000) reported that the maximum range of dorsiflexion measured with no rearfoot wedge was 85.91°. This decreased to 68.23° with a 3° rearfoot wedge, to 58.80° with a 5° wedge, and 51.66° with an 8° rearfoot wedge. However, the mean value cannot demonstrate the considerable inter-participant variation in the results. Even with an 8° rearfoot wedge the range of dorsiflexion was between 33°- 78°. This suggests that some feet may be more or less affected by an increase in the everted position of the rearfoot, and some are still within Root et al (1977) proposed normal range of dorsiflexion.

However, Halstead et al (2005) reported that there was little difference in the frontal plane movement of the rearfoot in feet classified with a limited or normal range of dorsiflexion from static examination. The calcaneus was everted relative to the tibia only 1.73° ($p = >0.05$) more in feet classified with limited hallux dorsiflexion (mean = 19.32°), than feet classified with a normal (mean = 39.35°) range of dorsiflexion. Although, Root et al (1977) stated that the normal range of dorsiflexion at the first metatarsophalangeal joint measured in RCSP is between 20°-30°. In consideration that the mean range of dorsiflexion measured for the group chosen to represent "limited" by Halstead et al (2005) was 19.32°, it questions whether the feet used by

Halstead et al (2005) are truly indicative of a limited classification. This may explain why there is not a significant difference in the magnitude of rearfoot eversion between the two groups tested.

Furthermore, contrary to Root et al (1977) some (Simon et al 2006, Carson et al 2001, MacWilliams et al 2003, Turner et al 2007) have demonstrated that the peak angle of dorsiflexion of the hallux relative to the first metatarsal during propulsion is less than 65°. The calcaneus was everted relative to the tibia during midstance, and then inverted during propulsion in all of the feet tested in these investigations. Although, the number of participants included in these investigations is quite small (less than n = 28), all are asymptomatic. Therefore providing further evidence to question whether pronation of the subtalar joint will cause a limited range of dorsiflexion at the first metatarsophalangeal joint or injury to it.

Root et al (1977) suggested that decreasing or preventing the subtalar joint from pronating during midstance, and/or propulsion through an orthotic device should enable the first metatarsophalangeal joint to dorsiflex to 65°. However, Halstead et al (2005) and Munteanu and Bassed (2006) found that placing the rearfoot into an inverted position does not increase the range of dorsiflexion at the first metatarsophalangeal joint. Munteanu and Bassed (2006) reported that the range of dorsiflexion at the first metatarsophalangeal joint increased only 1.90 ($p = >0.05$) when the foot was placed in a Blake style 30° inverted orthotic. Although, Munteanu and Bassed (2006) used feet classified as pronated from the Foot Posture Index (Redmond et al 2006) which has largely un-validated ability at correctly predicting the function of the foot during walking (Barton et al 2011, Nielson et al 2008, Levinger et al 2011, Teyhen et al 2012). This suggests that possibly the pronated foot type used by Munteanu and Bassed (2006) may not be excessively pronated at the subtalar joint during walking, and therefore is a poor comparison to what Root et al (1977) hypothesised. However, the results from Halstead et al (2005) are in agreement with Munteanu and Bassed (2006). Halstead et al (2005) described how the range of dorsiflexion at the first metatarsophalangeal joint increased by only 0.1°, (p = >0.05) when a foot classified as limited as previously explained was placed in a 10° rearfoot medial wedge orthoses device.

2.4.7 Examination of limb length

Root et al (1977) proposed that any difference in limb length is abnormal. To compensate for this difference the subtalar joint will have to abnormally pronate. However, there is no description provided of whether the limb classified as long or short will abnormally pronate. As the human skeleton is rarely symmetrical, there could hypothetically always be a difference in limb length that is not necessarily problematic. This is in agreement with Brady et al (2003) relating to Friberg (1983), who proposed that 50% of population have a limb length discrepancy which is greater than 5mm, and Pappas and Nehme (1979) who suggested that a limb length discrepancy of up to 11mm is not a cause of symptoms.

There is no description of the examination protocol for the measurement of limb length by Root et al (1977). This could be because the examination protocol devised by Root et al (1917, 1977) primarily focused on the foot, and limb length is an extrinsic deformity. Brady et al (2008) and others (Woerman and Binder-Macleod 1984, Jonson and Gross 1997, Bloedel and Hauger 1995 and Blustein and D’Amico 1985) state that there are two main categories of the assessment of limb length; direct and in-direct.

Brady et al (2003) stated that direct methods of limb length can involve measurement using radiographic imaging, or a tape measure. However, radiographic imaging is rarely suitable for general clinical practice although it is the most reliable and accurate method. The tape measure method is non-invasive, easy to use, and aims to measure directly the length of the femur and or tibia. However, Brady et al (2003) highlighted there are numerous difficulties with this method. These include: the difficulty in identifying bony landmarks, particularly in larger individuals, failing to measure from the same exact position of the bony landmark for repeat measurements, clothing of the participant, and the actual position of the patient. These factors can all increase the error, and reduce the reliability of this examination method.

The examination of limb length with a tape measure is usually conducted with the participant lying down in a supine position. Woerman and Binder-Macleod (1984) reported poor validity of the tape measure method, with a difference of 3.5cm ($p=<0.05$) between the tape measure and radiographic measurement. Such differences would undoubtedly change treatment plans. In contrast, Hoyle et al (1981) report ICC = >0.895, and Jamaluddin et al (2011) report ICC = 0.924 indicating excellent inter-assessor reliability for the examination of limb length with a tape measure. The measurements obtained with the tape measure in Jamaluddin et al (2011) were only 1.95mm different to the measurements obtained from a Computerised Tomography scan. Although the range of measurements in Jamaluddin et al (2011) were between -3.17mm to 7.07mm which indicates that the tape measure under and over estimated the difference in limb length.

The in-direct methods use visual assessment, or palpation techniques to determine pelvic or shoulder height, therefore inferring that a limb length discrepancy will be visible via observation of these. The placement of blocks under the heel of the participant, and measurement with a pelvis measuring device is reported by Woerman and Binder-Macleod (1984) as a much more accurate examination technique, than tape measure. When compared to the measurements from radiographs the difference between the two measurements was only 0.412cm. Jonson and Gross (1997) reported very high ICC values of 0.87 for intra-, and ICC = 0.70 for inter-assessor reliability when placing blocks under the heel of the participant and determining when the pelvis was level.

Brady et al (2003), Hoyle et al (1991) and Subotnick (1981) reported that individuals complaining of low back pain, patello-femoral pain and plantar fasciitis were commonly classified with a limb length discrepancy. However, the relationship between a limb length discrepancy, and the cause of musculoskeltal injury remains inconclusive, or the how the biomechanical function of the foot, leg and lower limb change due to a difference in limb length. Bloedel and Hauger (1995) reported that the peak angle of calcaneal eversion relative to the tibia was only -0.4° (p =>0.05) greater in the longer limb, and the peak angle of calcaneal inversion relative to the tibia was only 0.3° (p=>0.05) greater in the short limb. The difference in limb length of the participants used in Bloedel and Hauger (1995) was 1.27cm-1.9cm, which exceeds the proposed normal difference in limb length by Pappas and Nehume (1979). This is in agreement with McCaw and Bates (1991), they describe how the subtalar joint of the longer limb will pronate more so to provide functional shortening of the limb. In contrast, Subotnick (1981) proposed that the subtalar joint of the shorter limb will pronate more during walking.

2.4.8 Contemporary descriptions and attempts at creating a new clinical model of foot and ankle biomechanics

Some (Redmond et al 2006, McPoil and Hunt 1995, Perry 1992, Dananberg 2000, Kirby 1989) have proposed new and alternative descriptions or models of the biomechanical function and assessment of the foot to the Root et al (1971, 1977) description. However, these new models (Redmond et al 2006, McPoil and Hunt 1995, Perry 1992, Dananberg 2000, Kirby 1989) lack the in-depth and structured information that the Root et al (1971, 1977) description provides, and have failed to be full adopted into clinical practice.

The Foot Posture Index (Redmond et al 2006)

The "Foot Posture Index" (Redmond et al 2003, Redmond et al 2006) has capitalised on the need for a static examination protocol that aims to accurately define overall foot posture. The Foot Posture Index a simple method for classifying how pronated, neutral or supinated the foot is during static, weight bearing double limb stance (Redmond et al 2006). The Foot Posture Index classifies six sections of the foot. These are: talar head palpation, superior and inferior lateral mallelous curvature, calcaneal frontal plane position, bulge in the talo-navicular joint, congruence of the medial longitudinal arch, and the degree of adduction or abduction within the forefoot compared to the rearfoot. Redmond et al (2006) stated that each stage is graded on a scale from -2 for supinated, to +2 for pronated. Overall, it will produce a score of between -12 (supinated), and +12 (pronated).

This categorisation is then divided into:

- Supinated (-1 to -4) and Highly Supinated (-5 to -12)

- Neutral (0 to +5)

- Pronated (+6 to +10) and Highly pronated (+10 to +12)

(Redmond et al 2006).

Redmond et al (2008) proposed from a series of separate investigations which in total includes 619 asymptomatic participants what scores from the Foot Posture Index represent the normal foot. Overall, Redmond et al (2008) stated that a Foot Posture Index score of +4 represents the ideal normal foot. Although, the range of Foot Posture Index scores for a normal foot can be between +7 to +1, and is therefore a neutral to mildly pronated foot. Redmond et al (2008) stated that a Foot Posture Index score range of between -3 to +10 could infer a potential predisposition to pathology or development of injury. A score of between <-3 to >+10 indicates a more severely pronated or supinated foot, which is commonly associated with pathology or the development of injury. The use of a range of values to represent the normal, pre-disposed to injury or pathological foot is a definite step forward from the preciseness of the Root et al (1977) based measurements. The intra- and inter-assessor reliability of the Foot Posture Index has been reported as good for both asymptomatic and symptomatic populations. Cornwall et al (2008) reported ICC values of up to ICC = 0.937 for intra, and up to ICC = 0.655 for inter-assessor reliability. Cornwall et al (2008) suggested that an individual becomes significantly more reliable and proficient at conducting the Foot Posture Index examination with more practice. However, the Foot Posture Index scores in Cornwall et al (2008) changed by only 0.1 across all assessors between assessment 1 and 2. This is not enough to change the Foot Posture Index classification of the foot. Using the 8 stage criteria of the Foot Posture Index, Evans et al (2003) reported high ICC values for intra-assessor reliability with ICC = 0.809, although comparatively lower ICC values for inter-assessor reliability with 0.58.

Redmond et al (2006) proposed that the aim of the Foot Posture Index (Redmond et al 2006) is to provide a valid and reliable classification tool,that can be used to predict how a foot will function during walking. However, the ability of the Foot Posture Index to predict the movement and function of the foot during walking remains inconclusive. For example, Chuter (2010) reported r values of up to 0.92 ($p = <0.05$) for the correlation between the Foot Posture Index score and the peak angle of the calcaneal eversion relative to the tibia during the stance phase of walking. In contrast, Barton et al (2011) reported low to moderate r values of only $r = 0.230$ ($p=0.370$) for the same correlation. r values in Barton et al (2011) dramatically improved when correlations were made between the Foot Posture Index and any foot parameter that was measured relative to the laboratory rather than the tibia. For example, for the correlation between the Foot Posture Index for the range of eversion of the calcaneus relative to the tibia was $r = -0.022$ ($p=0.640$). When compared relative to the tibia $r = 0.614$ ($p=0.009$). Barton et al (2011) suggested that this may because using foot parameters relative to the laboratory focuses on just the movement of that segment, which will be more sensitive to foot motion.

The relationship between the Foot Posture Index and the movement of the midfoot during walking is similarly inconclusive. Nielson et al (2008) reported $r^2 = 0.132$ ($p <0.0001$) between the Foot Posture Index and the minimal height of the navicular, and $r^2 = 0.450$ ($p <0.0001$) for the measurement of the navicular drop. Although, the advantage of Nielson et al (2008) is that they measured 280 feet, there are several limitations of the investigation. Such as the use of 2D video analysis, and the measurement of the navicular is not disclosed. There is similar poor correlation between the Foot Posture Index classification and plantar pressure data (Teyhan et al 2011, Sanchez-Rodriguez et al 2012). For example, Teyhan et al (2011) reported r values between the Foot Posture Index classification and the peak pressure under the hallux of r = <0.26, first metatarsal r = < -0.23 and lateral hindfoot r = - 0.22.

The tissue stress model (McPoil and Hunt 1995)

The tissue stress model developed by McPoil and Hunt (1995), aimed to instruct clinicians how to identify the cause of tissue stress that has resulted in the development of the presenting injury. Through various methods of conservative treatment the aim is to reduce this stress to a tolerable level, and therefore reduce the symptoms a patient presents with to a tolerable level. The tissue stress model (McPoil and Hunt 1995) differs from the Root et al (1977) description because it aims to assess and treat the presenting injury, rather than just identify a structural deformity of the foot. However, the protocol for the assessment of the foot in the tissue stress model as described by McPoil and Hunt (1995) lacks the in-depth structure, and design of the Root et al (1971, 1977) protocol. It primarily offers a brief critique of some aspects of the Root et al (1971, 1977) protocol for the examination of the subtalar joint, and it offers no new methods. There have also not been any conclusive developments of the tissue stress model since its initial publication in 1995. Some elements of it are discussed in some text books (Brukner and Khan 2009), but it is not a widely used model in clinical practice.

The sagittal plane theory (Perry 1992, Dananberg 2000)

Perry (1992) stated that the facilitation of sagittal plane motion within the foot, leg and lower limb is maintained by three anatomical rockers. These are situated within the foot and help to maintain a pendulum type movement of the foot, leg and lower limb in the sagittal plane during walking. Perry (1992) stated that at initial contact, the *"heel rocker"* will maintain forward progression of the foot and leg. The round posterior surface of the calcaneus will aid the movement of the centre of pressure, and ground reaction vector forwards from the heel through the foot. The second rocker is the "*ankle rocker,"* Perry (1992) proposed that this will aid the forward facilitation of the tibia and lower limb above the foot, which can remain fixed to the floor during single limb stance. The third rocker is the *"forefoot rocker"* which Perry (1992) described how with heel lift, body weight can pivot over the first metatarsophalangeal joint as it dorsiflexes.

However, the sagittal plane theory is predominantly theoretical ideas with largely un-validated use clinically. Lundgren et al (2007) and others (Manter 1941, Nester et al 2003, Nester et al 2006, Leardini et al 2007, Hunt et al 2001a, Cornwall and McPoil 1999a, Lundberg et al 1989a, Lundberg et al 1989b, Lundberg et al 1989b) have all demonstrated that the joints of the foot move in the sagittal, frontal and transverse planes, and that movement in the frontal and transverse planes should not be ignored. Neither Perry (1992), nor Dananberg (2000) provide a protocol for the static or dynamic biomechanical assessment of the foot. The static assessment of the range of dorsiflexion at the ankle joint and first metatarsophalangeal joint as Root et al (1971, 1977) described have been criticised for questionable validity and little relation to dynamic function of the foot (Rome 1996, Halstead and Redmond 2006, Cornwall and McPoil 1999b, Munteanu and Bassed 2006, Hopson et al 1995).

The Kirby skive technique (Kirby 1989)

The “Kirby skive technique” (Kirby 1989) is an orthotic manufacturing technique for creating a unique design of an inverted varus heel cup. Kirby (1989) proposed that rotational equilibrium across the subtalar joint axis is where there is a balance in pronation and supination moments around the axis of the subtalar joint. This is hypothesised to be the optimum position of the foot to function normally. The identification of the subtalar joint axis in a non-weight bearing assessment as described by Kirby (1989) involves application of force onto the plantar surface of the foot in the proposed location of the subtalar joint axis. When no motion of the foot is evident, it represents the position of the axis of the subtalar joint and small pen marker crosses are drawn onto the foot. Kirby (1989) stated that application of pressure medial to the axis of the subtalar joint, would create a supination moment, and lateral to the axis of the subtalar joint, would create a pronation moment. However, this procedure is inherently unreliable due to patient pro-prioception and muscular contraction response. Therefore it would make it very difficult to conduct accurately. The proposed importance and use of identifying the subtalar joint axis is predominantly based on Kirby (1989) own clinical experience, and theoretical ideas of which the validity and reliability of this procedure is yet to be properly critiqued. The Kirby skive technique (Kirby 1989) is very limited, and its use sporadic among clinicians. It is also not supported by evidence based reliable and peer reviewed research, and it is used almost exclusively within podiatry.

2.4.9 A summary of the key points derived from a critical review of the Root et al (1971, 1977) protocol for conducting a static based biomechanical assessment of the foot, and whether the measurements from this assessment protocol can predict the movement and function of the foot during the gait cycle

1. Many authors have reported poor intra- and inter-assessor reliability of the examinations included within the Root et al (1971, 1977) assessment protocol. The reliability of an examination infers its clinical value. The large variation in the measurements obtained between different measurements by the same or different assessors indicate they cannot be used to make accurate clinical judgements. This indicates that procedures used for the classification of foot deformity, development of a treatment rationale or orthotic prescriptions are not reliable.

2. Root et al (1971, 1977) proposed that the measurements obtained from conducting a static based biomechanical assessment of the foot would be able to predict the movement and function of the foot during the gait cycle. However, in those examinations that have been tested, many have reported that there is not a strong relationship between the measurements obtained from a static examination of the foot, and the kinematics of the foot during the gait cycle.

3. Root et al (1971, 1977) proposed that the measurements obtained from conducting a static based biomechanical assessment of the foot can be used to classify a foot with a structural deformity. Feet classified with a structural deformity are described by Root et al (1977) to present with abnormal kinematic motion during the gait cycle, which is a cause of injury and deformity. However, some investigations using large cohorts of asymptomatic participants have classified feet with at least one of these structural deformities, indicating that they are not a cause of injury.

4. There is a definite lack of evidence presented by Root et al (1971, 1977) to support their description of how the measurements, or classification of a structural deformity of the foot obtained from a static biomechanical assessment, can predict the function of the foot during the gait cycle. Root et al (1977) did not provide any literature evidence, or the references used present many experimental methodological difficulties, which question the validity of the results obtained. However, there is also a dearth of literature describing the movement and function of feet classified with any of the structural deformities proposed by Root et al (1971, 1977).

5. Some (Redmond et al 2006, McPoil and Hunt 1995, Dananberg 2000, Kirby 1989) have proposed new examinations, or attempts to design a new clinical model of foot biomechanics. However, these do not present enough evidence based research to remove Root et al (1971, 1977) from clinical use, or for the development of a new clinical model that could be viably used by podiatrists in clinical practice.

6. Many have investigated the reliability and/or the validity of the different biomechanical examinations of the foot, but most have not precisely followed the Root et al (1971, 1977) assessment protocol. Therefore some elements of it have not been properly tested. There is also a lack of evidence to suggest that these investigations have considered what clinicians are currently using in clinical practice for conducting a biomechanical assessment of the foot.

2.5 A summary of a critical review of the Root et al (1971, 1977) description

This chapter has demonstrated that there are many key difficulties with the Root et al (1971, 1977) description. It questions the clinical efficacy of using it as a basis for the biomechanical assessment of the foot, or describing the function of the foot during the gait cycle.

The results from many investigations strongly indicate that the Root et al (1977) description of the function of the normal foot during the gait cycle is incorrect. The considerable inter-participant variation in the angle, and range of motion of the joints within the foot in individuals that are asymptomatic, indicates it is not possible to define a normal foot as Root et al (1971, 1977) proposed.

There is a lack of evidence provided by Root et al (1971, 1977) to support their descriptions of the kinematics of the midtarsal joint and forefoot during the gait cycle. Their description is based predominantly on hypothesised ideas which are not supported by more recent literature. The results from many investigations, in particular those (Lundberg et al 1989a, Lundberg et al 1989b, Lundberg et al 1989b, Nester et al 2006 and Lundgren et al 2007) that have used intra-cortical bone pins for measuring the kinematics of the foot, report that these regions of the foot are much complex than Root et al (1971, 1977) described.

However, there are two key limitations with some more recent investigations. First, most have used predominately small cohorts, and therefore cannot describe the extent of the inter-participant variation in the movement of the joints of the foot during the gait cycle. Second, some investigations using skin mounted marker systems have overly simplified the measurement of foot kinematics. For example, some have only divided the foot into separate forefoot and rearfoot rigid segments. This method cannot demonstrate the amount of motion within these segments. Multi-segment models of the foot that incorporate a midfoot, lateral forefoot, and medial forefoot rigid segments might provide a much better representation of the kinematics of the foot.

Root et al (1971, 1977) proposed that the measurements obtained from using their protocol for the biomechanical assessment of the foot, would be able to classify a foot with a structural deformity and predict how it will move during the gait cycle. However many have reported that these examinations are not reliable and cannot predict the function of the foot during the gait cycle. Some (Garbalosa et al 1994, Buchanan and Davis 2005, McPoil et al 1988) investigations using asymptomatic participants have classified feet with at least one structural deformity of the foot. This questions the proposed relationship between these deformities and the cause of injury.

There is a dearth of literature that has investigated some aspects of the Root et al (1971, 1977) assessment protocol. The experimental methods used by some (McPoil and Cornwall 1994, McPoil and Cornwall 1996a, Jones and Curran 2012, Allen et al 2004, Harradine and Bevan 2000, Hopson et al 1995, Roukis et al 1996, Pierrynowski and Smith 1996) also question the validity of their results obtained, and whether any definitive conclusions can be derived from their research. There is also no evidence to suggest that any of the investigations that have examined the reliability, or validity of the static examinations of the foot have considered what podiatrists are currently using in clinical practice. Assessment methods may have changed from the original description provided by Root et al (1971, 1977). Therefore, there is a need for further investigations to determine if and how the Root et al (1971, 1977) description is still used in practice, and what biomechanical examinations of the foot are routinely used by podiatrists in clinical practice.

Overall, this indicates that further investigations are required to test the Root et al (1971, 1977) description. This will aim to determine the clinical value of the measurements obtained from their assessment protocol, and the accuracy of their description of the function and movement of the foot during the gait cycle.

Two research questions were developed from this critical review of Root et al (1971, 1977), with the aim of determining:

Research Question 1:

Does the Root et al (1977) description of the movement and function of the "normal" foot during the gait cycle concur with the kinematic data of the foot and leg collected from asymptomatic participants?

Research Question 2:

Can the measurements obtained from a static based biomechanical assessment of the foot predict the movement and function of the same foot during the gait cycle?

The work in this thesis seeks to answer these questions and thus investigate to which the Root et al (1971, 1977) description is fit for purpose.

CHAPTER THREE - AIMS AND HYPOTHESES OF THIS INVESTIGATION

3.1 Chapter Overview

This chapter expands the two research questions developed for this investigation. The experimental design used in this investigation was specifically designed to accommodate the Root et al (1971, 1977) descriptions. This aimed to ensure that what they were proposing could be thoroughly tested in the most accurate, and complete method. From the literature review, two research questions were developed.

For Research Question 1, it focused on the description of the function of the foot during walking. Root et al (1977) proposed a series of concepts about how the foot will move during walking. However, these concepts do not represent formal hypotheses, and are therefore described throughout this thesis as a "Root et al hypothesis."

For Research Question 2, it focuses on how Root et al (1971, 1977) proposed that the measurements from a static examination can predict how the foot will move during walking. From this it was possible to generate a series of formal directional hypotheses, as Root et al (1971, 1977) proposed that there is a clear relationship between these variables and this could then be tested appropriately.

Where possible a quotation from the Root et al (1971, 1977) text is included to demonstrate that the Root et al hypothesis or hypothesis is a faithful interpretation of the Root et al (1971, 1977) description.

From these it was possible to determine what type of data will be required. To design a protocol for the collection of foot kinematic data there is a literature review of some of the most commonly used multi-segment models of the foot used in clinical gait analysis. It describes how the different segments of the foot are defined and measured and what methods have been used to try and reduce possible sources of error from using skin mounted retro-reflective markers.

3.2 Research Question 1

Does the Root et al (1977) description of the movement and function of the "normal" foot during the gait cycle concur with the kinematic data of the foot and leg collected from asymptomatic participants?

Root et al Hypothesis 1: At initial heel contact the subtalar joint is supinated.

Quote from Root et al (1977), p.137: *"At heel strike, the subtalar joint is slightly supinated."*

Root et al Hypothesis 2: At initial heel contact the midtarsal joint is pronated (dorsiflexed and abducted) around the oblique axis, and supinated (inverted) around the longitudinal axis.

Quote from Root et al (1977), p.139: *"At heel strike, the forefoot is supinated (inverted) around the longitudinal axis of the midtarsal joint and it is simultaneously pronated around the oblique axis."*

Root et al Hypothesis 3: The calcaneus will evert from neutral 4-6°during the contact phase.

Quote from Root et al (1977), p.137: *"the normal rearfoot reaches its maximum position of pronation at the end of the contact period, which corresponds with toe off of the opposite foot. At this point, the calcaneus is everted from neutral by approximately four to six degrees (4°-6°)."*

Root et al Hypothesis 4: The subtalar joint will stop pronating when forefoot contact is made and supinate during midstance.

Quote from Root et al (1977), p.129: *"The skeletal foot is converted from a mobile adaptor to a rigid level necessary for propulsion. This is accomplished by continual subtalar joint supination, which moves the foot out of its pronated position (at the end of the contact period) into a supinated position prior to heel lift."*

Root et al Hypothesis 5: The midtarsal joint will pronate (dorsiflex, evert and abduct) during midstance, and will reach a position of maximum pronation at heel lift.

Quote from Root et al (1977), p.140: *"When the subtalar joint reaches its neutral position, shortly before heel lift, ground reaction locks the midtarsal joint in its fully pronated position around the longitudinal axis."*

Root et al Hypothesis 6: At heel lift the subtalar joint will reach its neutral position.

Quote from Root et al (1977), p.137: *"Shortly before heel lift, the subtalar joint reach its neutral position."*

Root et al Hypothesis 7: During the phase of propulsion the subtalar joint will be supinating.

Quote from Root et al (1977), p.137: *"During the propulsive period, the leg continues to externally rotate, the subtalar joint supinates, and the calcaneus inverts until just before toe off."*

Root et al Hypothesis 8 - During the phase of propulsion, the midtarsal joint will remain in a pronated position (everted) around the longitudinal axis, and it will supinate (plantarflex and adduct) around the oblique axis.

Quote from Root et al (1977), p.140: *"During propulsion, the midtarsal joint normally remains locked around its longitudinal axis."*

Root et al Hypothesis 9: The first metatarsophalangeal joint will dorsiflex between 65°-75° during propulsion.

Quote from Root et al (1977), p.56: *"In the final stage of propulsion, the tibia is tilted approximately 45° forward from vertical and the foot is plantarflexed at the* *ankle about 20°. The angle between the sole of the foot and the floor thus approximates 65° while the hallux is being firmly held against the ground."*

Root et al Hypothesis 10: During the swing phase the subtalar joint will supinate, and the midtarsal joint will supinate around its longitudinal axis.

Quote from Root et al (1977), p.144: *"The entire foot moves at the subtalar joint during the swing phase of gait."*

Root et al Hypothesis 11: During the contact phase there is a greater range of kinematic motion evident in the forefoot, compared to the amount of motion evident during the phases of midstance and propulsion.

Quote from Root et al (1977), p.129: *"The foot is normally a mobile adaptor during the contact period. The pronated subtalar joint position provides skeletal mobility... The skeletal foot is converted from a mobile adaptor to a rigid lever necessary for propulsion."*

3.3 Research Question 2

Can the measurements obtained from a static based biomechanical assessment of the foot predict the movement and function of the same foot during the gait cycle?

Hypothesis 1: NCSP will represent the position of the subtalar joint during midstance prior to heel lift in the normal foot

Quote from Root et al (1977), p.137: *"Shortly before heel lift, the subtalar joint reaches its neutral position."*

Hypothesis 2.a: The normal range and angle of dorsiflexion that should be measured at the ankle joint in a static examination, and during midstance in the normal foot is 10°. Feet that do not demonstrate 10° of dorsiflexion at the ankle joint in static examination, will not dorsiflex to 10° at the ankle joint during midstance.

Quote from Root et al (1977), p.37: *"The minimum range of ankle joint dorsiflexion necessary for normal locomotion is 10° of dorsiflexion."*

Hypothesis 2.b: Feet that cannot demonstrate 10° of dorsiflexion in the static examination of the ankle joint, will pronate at the subtalar joint during midstance

Quote from Root et al (1977), p.38: *"The ankle joint must provide approximately 10° of dorsiflexion for the leg and trunk to move to this normal position without lifting the heel prematurely or pronating the foot excessively."*

Hypothesis 3: A foot which is classified with a rearfoot varus deformity defined from static examination will pronate, and remain in a pronated position at the subtalar joint during midstance. This is compared to a normal foot which will supinate during midstance

Quote from Root et al (1977), p.313: *"Rearfoot varus is an example of an etiological factor which causes abnormal pronation while the heel and forefoot are in contact with the ground. The need for pronatory compensation vanishes at heel lift, and the foot is able to make a partial recovery from its abnormally pronated position."*

Hypothesis 4: A foot classified with a rearfoot valgus deformity defined from static examination will pronate at the subtalar joint throughout the stance phase of the gait cycle. This is compared to a normal foot which will pronate at the subtalar joint during the contact phase, and supinate at the subtalar joint during midstance and propulsion.

Quote from Root et al (1977), p.156: *"In any rearfoot valgus deformity, the calcaneus is everted when the subtalar joint is in its neutral position."*

Hypothesis 5: The normal range or angle of dorsiflexion that should be measured at the first metatarsophalangeal joint in a static examination, and during propulsion in the normal foot is between 65°- 75°. In feet that dorsiflex less than 65° at the first metatarsophalangeal joint during propulsion, the subtalar joint will be in a pronated position during midstance and propulsion.

Quote from Root et al (1977), p.56: *"The minimum range of 1st metatarsophalangeal joint dorsiflexion necessary for normal locomotion approximates 65°-75°."*

Quote from Root et al (1977), p.60: *"Those conditions, which have been recognised as causes of abnormal restriction of 1st metatarsophalangeal joint motion are: 6. Eversion of the foot during propulsion which is caused by abnormal subtalar joint pronation."*

Hypothesis 6a: A foot classified with a plantarflexed first ray deformity defined from static examination will pronate at the subtalar joint, and supinate at the midtarsal joint during propulsion. This is compared to a normal foot which will supinate at the subtalar joint, and pronate at the midtarsal joint during propulsion.

Quote from Root et al (1977), p.173: *"... and moderate plantarflexed first ray deformities are two examples of deformities which produce active subtalar joint pronation during propulsion."*

Quote from Root et al (1977), p.140: *"Deformities that maintain the foot in a pronated position, forefoot valgus deformity, and mild plantarflexed first ray* *deformity all prevent normal locking of the forefoot around the longitudinal axis of the midtarsal joint prior to propulsion."*

Hypothesis 6b: A foot classified with a dorsiflexed first ray deformity defined from static examination will not dorsiflex more than 65° at the first metatarsophalangeal joint during propulsion. This is compared to a normal foot which will dorsiflex between 65-75° at the first metatarsophalangeal joint during propulsion.

Quote from Root et al (1977), p.361-363: *"Therefore, both the congenital and acquired dorsiflexed deformities of the 1st ray limit the range of dorsiflexion because the 1st ray cannot plantarflex normally during propulsion."*

Hypothesis 7a: A foot classified with a forefoot valgus deformity defined from static examination will pronate at the subtalar joint, and supinate at the midtarsal joint during propulsion. This is compared to a normal foot which will supinate at the subtalar joint, and pronate at the midtarsal joint during propulsion.

Quote from Root et al (1977), p.313: *"Forefoot valgus is a deformity which causes abnormal compensatory pronation during propulsion."*

Quote from Root et al [1977], p.314: *"The greater the degree of forefoot valgus deformity, the larger the range of compensatory pronation at the subtalar joint."*

Hypothesis 7.b: A foot classified with a forefoot varus deformity defined from static examination will pronate at the subtalar joint throughout the stance phase of the gait cycle, and the subtalar joint will be in a maximally pronated position during propulsion. This is compared to a normal foot which will pronate at the subtalar joint during the contact phase, and supinate at the subtalar joint during midstance and propulsion.

Quote from Root et al (1977), p.313: *"Forefoot varus, however is a deformity which produces abnormal compensatory pronation throughout the stance phase of the gait cycle."*

Quote from Root et al (1977), p.313: *"The extent of the abnormal pronation is limited only by the range of motion at the subtalar joint."*

Hypothesis 8: The longer limb will demonstrate different re-supination characteristics at the subtalar joint during the phase of midstance, and propulsion compared to those with equal limb length.

Quote from Root et al (1977), p.301: *"Some common congenital and developmental deformities of the lower extremities extrinsic to the foot are also compensated by abnormal pronation of the foot. The most common deformities in this class are: 7. Inequality of limb length."*

3.4 Data required to test Research Question 1 and 2

In order to provide conclusive answers to Research Question 1 and 2, two sets of data from asymptomatic participants are required:

Data set A: Anthropometric data from a static based biomechanical assessment of the foot

Data set B: Instrumented gait analysis of the foot and leg

To develop a protocol for the collection of Data set A, and Data set B it was necessary to:

1. Determine if the Root et al (1971, 1977) description and what examinations from the Root et al (1971, 1977) assessment protocol are still used by podiatrists in clinical practice. This is addressed through a Delphi Technique investigation described in Chapter 4.

2. Determine what multi-segment model of the foot is the most suitable for the measurement of foot and leg kinematics for this investigation. This was addressed through a literature review presented in the next section of this chapter.

3.5 Multi-segment models of the foot for the measurement of foot kinematics

For the measurement of the kinematics of the foot, many (Leardini et al 2007, Moseley et al 1996, Hunt et al 2001a, Rattanaprasert et al 1999, Kitaoka et al 2006, MacWilliams et al 2003, Nester et al 2007, Jenkyn and Nicol 2007, Simon et al

2006, DeMits et al 2012, Carson et al 2001) have developed, designed, and tested various multi-segment models of the foot using retro-reflective markers (markers) attached to the skin surface of the foot. These are commonly described as "foot models".

Bishop et al (2012) stated that the aim of multi-segment models of the foot is to provide a simplification of the complex anatomy of the foot. They aim to represent the different bones, or collectively many bones within the foot to represent a region of the foot. Some foot models divide the foot into only two rigid segments commonly to represent the rearfoot and forefoot (Hunt et al 2001a, Kitaoka et al 2006, Rattanaprasert et al 1999, Moseley et al 1996). Others offer a much more complex approach, and divide the foot into three (Leardini et al 2007, Carson et al 2001), four (Jenkyn and Nicol 2007, Nester et al 2007), five (Simon et al 2006) or eight (MacWilliams et al 2003) rigid segments.

Bishop et al (2012) described how there are no specific scientific standards for how rigid segments of the foot should be defined. To determine the position and orientation of the local co-ordinate system to define a rigid segment within the foot most foot models use anatomical landmarks. However, Bishop et al (2012) emphasised that there is little consensus on what anatomical landmarks should or should not be used. They described how it is difficult to determine some landmarks from the skin surface. The irregular shape of some of the bony tuberosities can cause some markers to not attach sufficiently well to the proposed anatomical feature. Therefore, they will move during walking trials, and not be representative of the actual movement of that segment, or bone.

Bishop et al (2012) suggested that those proposing a new foot model should adhere to certain standards, and include some key details about the development and definition of the different segments. This includes the reliability, and accuracy of marker placement, how the position and orientation of the segment co-ordinate system are defined, and the process for the calculation of joint angles between rigid segments. The process for determining what structures of the foot to measure individually or together can pose considerable problems (Nester et al 2007, Hunt et al 2001a). Attempting to measure all bones of the foot using skin mounted markers is neither wise, nor feasible. This is because some bones of the foot (i.e the talus) are not accessible from the skins surface, and others are too small to be individually accurately defined.

Investigations that have used intra-cortical bone pins (Nester et al 2006, Lundgren et al 2007, Lundberg et al 1989a, Lundberg et al 1989b, and Lundberg et al (1989c) inserted into some of the bones of the foot have demonstrated that there is a substantial amount of movement between the different joints of the foot. This was particularly evident within the midfoot and forefoot. This indicates that these articulations should be incorporated when possible into the measurement of foot kinematics and focus should not solely be on the rearfoot. Huson (1991), and others (Elftman 1960, Vogler and Bojson-Moller 2000, Huson 2000, Pohl et al 2006, and Wolf et al 2008) have reported that some bones in the foot move together in a similar pattern of motion. Therefore, many (Leardini et al 2007, Moseley et al 1996, Hunt et al 2001a, Rattanaprasert et al 1999, Kitaoka et al 2006, MacWilliams et al 2003, Nester et al 2007, Jenkyn and Nicol 2007, Simon et al 2006 and Carson et al 2001) have proposed that modelling some of the bones of the foot together to represent a single rigid segment is a viable technique for the measurement of intricate foot kinematics. This has proven very useful when it is not possible to isolate specific bone movement. Overall, this has resulted in the creation of three main segments within the foot. They are commonly described as the rearfoot, midfoot and forefoot. In some instances, these segments have been divided into separate rigid segments as described by some (DeMits et al 2012, MacWilliams et al 2003, Nester et al 2007, Jenkyn and Nicol 2007).

However, Nester et al (2007) and Cappozzo et al (2005) stated that over simplifying the complex anatomy of the foot can be equally as problematic. This is because it can result in the failure to measure some important bones of the foot. If a segment contains more than one individual bone, this segment is not technically a rigid structure. This can also result in the movement of the markers that define that segment to move relative to each other which will violate the assumption of a rigid segment. Nester et al (2007) proposed that placing markers on rigid plastic plates will reduce the within marker movement. Therefore, movement from the skin is one overall movement of the plate, and not individual marker movement. This should help to improve the representation of the segment as “rigid.” This is demonstrated by the results from Nester et al (2007). They reported that in most instances, particularly for the measurement of midfoot and forefoot kinematics the use of rigid plastic plates to define a segment, provided a better representation of the movement of that segment than individual skin mounted markers.

Leardini et al (2005) and Reinschmidt et al (1997) stated that the primary source of error when measuring kinematics with skin mounted markers is skin movement artefact. This can result in movement of a segment being measured that is not indicative of the bone it is proposed to be representing. This is because the marker is moving with the skin, and not with the bone. There have been many investigations (Karlsson and Tranburg 1999, Fuller et al 1997, Cappozzo et al 2005, Leardini et al 2005, Della Croce et al 2005, Angeloni et al 1993, Reinschmidt et al 1997) that have described, and demonstrated the substantial errors caused by skin movement artefact when using skin surface mounted markers. All of these investigations reported that when deciding on the placement of skin mounted markers there were two important factors to consider. These are if there is any underlying soft tissue movement, and how close the marker is to any joint margins, or overlaying and bony prominences. For example, the importance of carefully selecting the placement of markers was highlighted by Karlsson and Tranburg (1999). They stated that in the measurement of the kinematic movement of the knee joint, the greatest deviation recorded between skin and intra-cortical bone mounted markers was when markers were placed on joint margins or on bony tuberosities surrounding the joint. This was predominantly dependent upon the angle, and velocity of joint movement.

For the measurement of foot kinematics, Nester et al (2007) and Reinschmidt et al (1997) reported that individual skin mounted markers, and markers attached to plastic rigid plates provided to some extent a comparable representation of the segment/bone they were representing, when compared to bone anchored markers. For example, Nester et al (2007) described that the maximum difference between bone anchored markers, and skin mounted markers was greater than 3° for 100% of all comparisons. It was greater than 7° in 73% of the comparisons. Although these differences would appear quite large, there were no consistent over or under estimation in the range of motion by either skin based method in comparison to the bone pin data. Differences between protocols were planal specific and different for different segments.

The second source of error is marker oscilliation, or vibration of the marker itself. This appears to be directly related to the size, and weight of the marker. Karlsson and Tranburg (1999) described how markers with a large diameter, and greater mass demonstrated a smaller marker resonance frequency error than markers with a small diameter and mass. Karlsson and Tranburg (1999) reported that a marker with a 30mm diameter, and a mass of 3.4g had a marker resonance frequency of only 23Hz when attached to the tibia. In contrast, a marker with the diameter of 19mm, and a mass of 0.8g had a marker resonance frequency of 45Hz. However, due to the small surface area of the foot, large markers are unlikely to be suitable for measuring foot kinematics due to cross marker interference during data collection. One possible solution to this is to increase the surface area of the marker base instead. This is a technique used by Angeloni et al (1993). They reported that markers that were attached directly onto the skin in the measurement of the kinematic movement of the thigh and shank were consistently subjected to larger displacements, than markers placed on rigid plastic plates. In consideration of the large muscle mass surrounding this area of the lower limb, it would suggest that if this technique can reduce movement here, it is also a viable option for measuring foot kinematics.

Measurement of rearfoot motion

The measurement and definition or rearfoot motion commonly includes the movement of the calcaneus relative to the tibia. As it is not possible to measure the movement of the talus using skin mounted markers, researchers have had to adopt a different method that can robustly represent the movement of this region of the foot. The movement of the calcaneus relative to the tibia has proved to be a suitable, reliable, and as accurate as possible method to represent the movement of the ankle and subtalar joints. It is a technique that has been adopted by many (Kitaoka et al 2006, Leardini et al 2007, Carson et al 2001, Hunt et al 2001a, Moseley et al 1996, Rattanaprasert et al 1999, MacWilliams et al 2003). Siegler et al (1988) suggested that combining the measurement of the ankle and subtalar joints together to represent the rearfoot is a suitable option. This is because the greatest range of sagittal plane motion occurs at the ankle joint, and the greatest range of frontal plane motion occurs at the subtalar joint. Therefore the movement in these planes can be attributed to the corresponding joint. Agreeably, Lundgren et al (2007) reported that the range of sagittal plane motion of the calcaneus relative to the tibia was 17.0°, and the talus relative to the tibia was 15.3°. Although the range of sagittal plane motion of the calcaneus relative to the talus was 6.8°. However this is considerably less than between the talus and tibia.

In the frontal plane, Lundgren et al (2007) measured a similar range of motion at the ankle and subtalar joints during the stance phase of walking. The range of frontal plane motion of the talus relative to the tibia was 8.1°, and the calcaneus relative to the talus was 9.8°. Overall, the range of frontal plane motion of the calcaneus relative to the tibia was 11.3°. In relation to the results afore-mentioned the measurement of the calcaneus relative to the tibia would appear to be a good representation of the range of motion at the subtalar joint.

Measurement of midfoot motion

Attempting to isolate and measure the individual movement of the navicular or cuboid is described by some (Tweed et al 2005, Nester et al 2007) as not possible or valid without the use of intra-cortical bone pins. This is due to the small size of the bones, the substantial overlaying soft tissue structures, and the difficulty in identifying any suitable anatomical landmarks to represent the shape of the cuboid. However, Elftman (1960), Huson (2000) and Tweed et al (2005) suggested that the navicular and cuboid function in unison as a midfoot segment Therefore, combining the measurement of the navicular and cuboid together as one rigid segment appears to be a suitable method for measuring this complex region of the foot when using skin surface mounted markers.

Some multi-segment models of the foot using skin mounted markers have included a midfoot rigid segment. They have measured its movement by placing either individual markers onto (Leardini et al 2007, DeMits et al 2012, MacWilliams et al 2003, Simon et al 2006) or a rigid plastic band overlaying (Nester et al 2007) the navicular and cuboid. Others (Carson et al 2001, Rattanaprasert et al 1999, Hunt et al 2001a, Kitaoka et al 2006, Pohl et al 2006) have suggested that the measurement of the movement of the forefoot relative to the rearfoot provided a good representation of midfoot movement. Although Hunt et al (2001a) suggested that this technique cannot accurately represent the complex anatomy of the midfoot and is more representative of forefoot motion. The measurement of the navicular and cuboid together as one rigid segment can produce some technical difficulties. First, Lundgren et al (2007) reported that there is a considerable range of motion between the navicular and cuboid. Therefore, indicating that it would be unwise to model these bones together as one rigid segment. Second, which is in relation to this movement between navicular and cuboid, is that the movement between these bines could be important in the function of the foot. However, the range of motion of the navicular relative to the talus, and the cuboid relative to the calcaneus is much greater than between the navicular and cuboid. Third, the individual movements of the navicular, and cuboid could result in some markers placed on either bone to move relative to each other. Therefore, it will not be representative of a rigid segment. However, the technique used by Nester et al (2007) which included the placement of a rigid plastic band can help to reduce this.

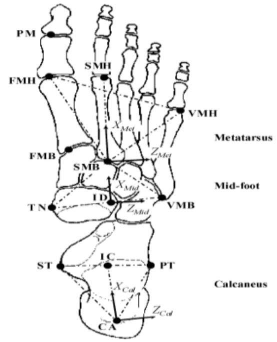
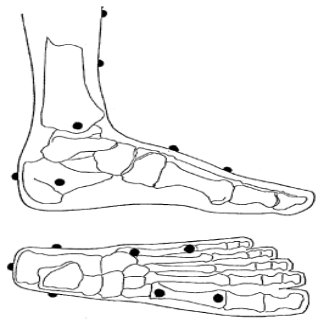
Nester et al (2007) also reported that this method provided a better representation and more accurate comparison when compared to intra-cortical bone pin markers.

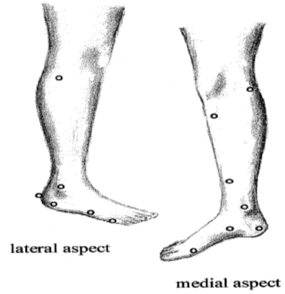
Measurement of forefoot motion

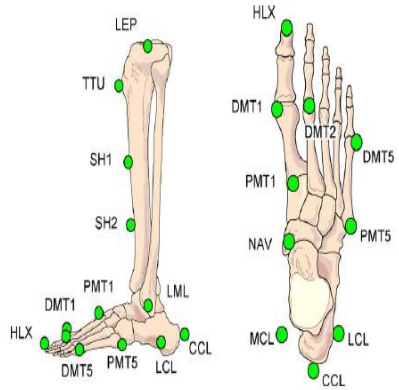
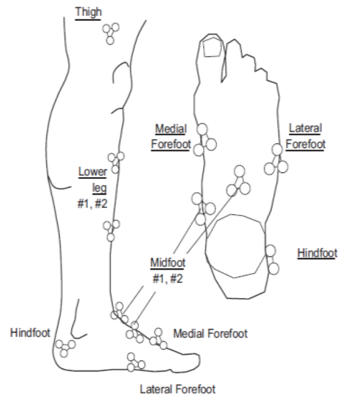
There are two main techniques used in the measurement of the forefoot when using skin mounted markers. These are the measurement of all five metatarsals together to represent one rigid segment as used in Hunt et al (2001a), Rattanaprasert et al (1999), Kitaoka et al (2006) and Carson et al (2001). Another technique is to separate the forefoot into medial, and lateral regions as used in Nester et al (2007), MacWilliams et al (2003), DeMits et al (2012) and Jenkyn and Nicol (2007). With intra-cortical bone pins it is possible to measure the individual movements of the metatarsals as used in Lundgren et al (2007), Lundberg et al (1989a), Lundberg et al (1989b), Lundberg et al (1989c), and Nester et al (2006).

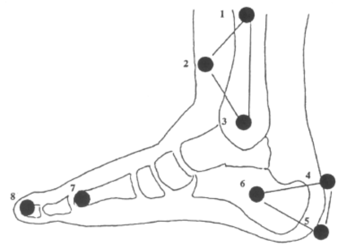
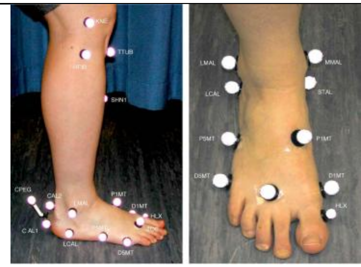
The results from Nester et al (2006) and Lundgren et al (2007) indicate that modelling all the metatarsals as one rigid segment would be unwise. This is because they reported that there is large variation in the range and direction of motion between the metatarsals and structures proximal to them. This inter-metatarsal motion will create intra-segmental motion. This will result in the the markers attached to the forefoot moving relative to each other. Therefore, indicating that defining the whole forefoot as one rigid segment is not representative of a “rigid” structure. However, Lundgren et al (2007) and Nester et al (2006) reported that there was a much greater range of motion between these metatarsals on the lateral aspect of the foot relative to the cuboid, than the metatarsals on the medial aspect of the forefoot relative to the cuneiforms. These regions of the foot also demonstrated individual movement patterns during walking. This would support the measurement of medial and lateral regions of the forefoot as used in DeMitts et al (2012), Nester et al (2007), and Jenkyn and Nicol (2007).

Table 3.1 describes some of the most commonly used foot models in clinical gait analysis and experimental studies with a summary of the key advantages and disadvantages of the design of each foot model. Although the key difficulties previously described should be taken into account when evaluating each foot model.

Investigation	**Rigid segments defined for this foot model**	**Advantages of foot model**	**Disadvantages of foot model**	**Photo/Picture of marker placement**
Leardini et al (2007)	1.Calcaneus 2.Midfoot (navicular and cuboid) 3.Forefoot (first to fifth metatarsals) 4 Leg (Tibia)	1. The placement of markers across the forefoot or midfoot enables a complete representation of these segments (for example markers are placed on the first, third and fifth metatarsals). 2. Anatomical landmarks chosen for the placement of markers are easily identifiable 3. The location of all markers were specifically selected with the aim to reduce skin movement artefact from soft tissue structures superficial to the skin. 4. Position and orientation of local co-ordinate system for each rigid segment defined from anatomical landmarks	1. The range of motion of the midfoot segment relative to the other segments is minimal which is in contradiction to results from Nester et al 2006 and Lundgren et al 2007). 2. No reliability or repeatability of marker set described. 3. Only 10 participants were included in this investigation.	
Kitaoka et al (2006)	1. Calcaneus 2. Forefoot (first to fifth metatarsals) 3. Leg (tibia)	1. Foot model tested in-shoe 2. Simple design of foot model, marker locations are easily identifiable for when a simple representation of the foot is required.	1. The holes cut in the shoes may change the structure of the shoe and therefore may not be representative of shod walking. 2. Markers would have to be placed on the foot after the participant was wearing the shoes, therefore investigator cannot determine anatomical landmarks of foot other than that displayed by the cut out sections of the shoes. 3. Simple representation of forefoot, only individual markers placed on the first and fifth metatarsals. 4. Unclear description as to how local co-ordinate system for each segment was defined.	

Hunt et al (2001a)	1.Calcaneus 2. Forefoot (first to fifth metatarsals) 3. Leg (Tibia)	1. Simple design of foot model and marker locations are easily identifiable for when a simple representation of the foot is required. 2. Position and orientation of local co-ordinate system for each rigid segment defined from anatomical landmarks 3. Between session repeatability was reported as good with CMC values for the rearfoot between 0.634- 0.916 and for the forefoot between 0.397- 0.977.	1. Movement of medial longitudinal arch segment measured in sagittal plane only. 2. To represent the forefoot, only one marker was placed on the first metatarsal and two markers on the fifth metatarsal. 3. To define the zero-reference position a vertical bisection line was drawn onto the posterior aspect of the calcaneus with participant non-weight bearing. The zero reference position was defined when this bisection line was in a vertical position(*)	
DeMits et al (2012)	1. Calcaneus 2. Midfoot (navicular and cuboid) 3. Lateral forefoot (second to fifth metatarsals) 4. Medial forefoot (first metatarsal) 5. Hallux 6. Leg (Tibia)	1. The forefoot is divided into medial and lateral regions. 2. Rigid plastic plate used to define part of lateral forefoot segment with the aim to reduce within marker movement and therefore provide a better definition of this segment as rigid. 3. Position and orientation of local co-ordinate system for each rigid segment defined from anatomical landmarks	1. Only 10 participants used in this investigation. 2. Hallux segment is defined with markers placed along the segment which would be subject to movement from inter-phalangeal movement within the hallux. 3. Definition of lateral forefoot segment maybe subject to within segment movement of markers because it includes second to fifth metatarsals which will move relative to each other during walking.	
Rattanaprasert (1999)	1. Calcaneus 2. Forefoot (first to fifth metatarsals) 3. Hallux 4. Leg (tibia)	1. Good between day and between walking trial reliability with r = 0.541- 0.970. 2. Data from foot model was capable of demonstrating that there is a difference in the kinematic movement of the foot in normal (asymptomatic) and abnormal (tibialis posterior dysfunction) patients. 3. Position and orientation of local co-ordinate system for each rigid segment defined from anatomical landmarks	1. Placement of a marker on the achilles tendon as part of rearfoot segment would be highly subject to soft tissue movement. 2. To represent the forefoot, only one marker was placed on the first metatarsal and two markers on the fifth metatarsal. 3. Only 11 participants were used for this investigation 4. To define the zero-reference position a vertical bisection line was drawn onto the posterior aspect of the calcaneus with participant non-weight bearing. The zero reference position was defined when this bisection line was in a vertical position(*)	

Simon et al (2006)	1. Calcaneus 2. Midfoot (navicular only) 3. Forefoot (first to fifth metatarsals) 4. Hallux.	1. Use of "functional segments" in an attempt to represent some of the articulations within each rigid segment. 2. This foot model design is proposed to be more applicable for the measurement of foot kinematics in feet with severe structural foot deformities than foot models using rigid modelling techniques. 3. Results of CMC values indicate good intra and inter assessor reliability and between days for the measurement of some angles. CMC values range from 0.383 to 0.984 for between day and 0.086 to 0.970 for between assessor. 4. Position and orientation of local co-ordinate system for each rigid segment defined from anatomical landmarks	1. Poor representation of midfoot with only one marker placed on the tuberosity of the navicular, therefore motion can only be measured relative to other structures on the medial aspect of the foot and only in the sagittal plane. 2. To measure the range of frontal plane motion between the forefoot and midfoot, the angle of all metatarsal heads were compared relative to the bases of all metatarsals. Measurement of the metatarsals is not indicative of midfoot movement 3. The talus is represented by the position of the subtalar joint axis. The position of the subtalar joint axis was defined from the rotation of the calcaneus in the frontal plane with a marker placed on the posterior aspect of the calcaneus on the insertion site of the achilles tendon which would be subject to skin movement.	
Jenkyn and Nicol (2007)	1. Calcaneus 2. Midfoot (Medial, central and lateral cuneiforms, navicular and cuboid) 3. Medial forefoot (first metatarsal) 4. Lateral forefoot (fifth metatarsal) 5. Leg (tibia)	1. Position and orientation of local co-ordinate system for each rigid segment defined from anatomical landmarks 2. Cluster markers used to represent rigid segment instead of individual markers. 3. The forefoot is divided into medial and lateral regions.	1. Only 12 participants were used for this investigation. 2. Marker placed overlaying the talus head was used to define the local co-ordinate system for the ankle and subtalar joints and the midfoot. This marker would be highly subject to skin movement artefact and palpation of the talus from the skin surface is difficult and not accurate. 3. Subtalar joint was defined as between the talus and midfoot which is anatomically incorrect. 4. Hindfoot marker was placed lateral to achilles tendon and may be subject to soft tissue movement superficial to the skin.	

MacWilliams et al (2003	1. Calcaneus 2.Midfoot (Talus/navicular/ cuneiform) 3. Cuboid, 4. Lateral forefoot (fifth metatarsal) 5. Medial forefoot (first metatarsal) 5. Medial toes (third phalange) 6. Lateral toes (fifth phalange) 7. Hallux 8. Leg (Tibia)	1. The patients tested in this investigation were children which indicate that the accuracy of their capture by three dimensional motion analysis is not compromised by the potentially small size of the foot being tested. 2. Complex rigid segmentation of foot, for example the division of the forefoot into separate medial and lateral forefoot segments. 3. Small standard deviation values and moderate to high CMC values for intra and inter-subject variability and repeatability of sagittal plane kinematics 4. Position and orientation of local co-ordinate system for each rigid segment defined from anatomical landmarks	1. No description of what markers define each segment. 2. Intra and inter-subject variability and repeatability only measured in the sagittal plane. Other foot models indicate that the measurement of sagittal plane motion is more reliable than frontal or transverse plane motion.	
Moseley et al (1996)	1. Calcaneus 2. Leg (Tibia)	1. Marker placement specifically designed to be minimally affected by skin movement artefact 2. Good reliability reported between different days of testing with r = >0.973 for all planes of motion.	1. No forefoot segment defined 2. Lab co-ordinate system used to define position and orientation of each rigid segment 3. The neutral position of the subtalar joint was used as the zero reference position and it was determined to be in a neutral position when the frontal plane angle of the calcaneus was vertical(*). 4. Only 14 participants used in this investigation.	
Carson et al (2001)	1. Calcaneus 2. Forefoot (first to fifth metatarsals) 3. Hallux 4. Leg (Tibia)	1. Good intra, inter and between days reliability for the measurement of rearfoot relative to the leg. 2. Simple design of foot model and marker locations are easily identifiable for when a simple representation of the foot is required. 3. Position and orientation of local co-ordinate system for each rigid segment defined from anatomical landmarks	1. Poor intra, inter and between day reliability for measurement of the hallux relative to the forefoot 2. Placement of a marker on the achilles tendon would be highly subject to soft tissue movement. 3. Hallux segment is only a vector not a true rigid segment. 4. Only 2 participants used in this investigation.	 Adapted from Stebbins et al (2006)#

Nester et al (2007)	1. Calcaneus 2. Midfoot (navicular and cuboid) 3. Medial forefoot (first-third metatarsal) 4. Lateral forefoot (fourth and fifth metatarsal) 5. Leg (tibia)	1. Markers mounted on rigid plastic plates reduce intra- marker movement within a segment 2. Markers mounted on rigid plastic plates to reduce marker oscillation 3. Markers mounted on rigid plastic plates aim to provide a better representation of a rigid segment. 4. Plate mounted markers consistently measured smaller mean and maximum differences in the measurements foot kinematics than markers placed directly on the skin when compared to bone mounted markers. 5. Each rigid segment was defined using a local co-ordinate system with the same position and orientation as each other.	1. Medial forefoot is measured with a plate overlaying the first, second and third metatarsals which could be subject to skin movement artefact from movement of underlying tendons (e.g extensor hallucis and digitorium longus.) 2. Plastic rigid band placed overlaying midfoot, will not be able to represent the complex movement of the navicular and cuboid.	

* Menz (1995) others (Menz and Keenan 1997, Keenan and Bach 2006, McPoil and Hunt 1995, Razeghi and Batt 2002, Keenan 1997) have reported that drawing a bisection line onto the posterior aspect of the calcaneus is highly error prone, not a reliable method and is not a valid representation of the frontal plane angle of the calcaneus or rearfoot. # No figure supplied from Carson et al (2001) of marker placement, but the same foot model was used in Stebbins et al (2006), therefore figure is adapted from this

CHAPTER FOUR – PRELIMINARY RESEARCH TO DETERMINE A PROTOCOL FOR THE COLLECTION OF DATA SET A

4.1 Chapter Overview

This chapter presents the preliminary research conducted in the preparation for the collection of Data Set A. It describes an investigation involving the Delphi technique which was used to determine if the Root et al (1971, 1977) description and what examinations from the Root et al (1971, 1977) assessment protocol are still used and how they are conducted by podiatrists in clinical practice. This ensured that the Root et al (1971, 1977) examinations to be included in Data Set A represented what podiatrists are currently using in clinical practice. A separate inter-assessor reliability study was conducted using four of the most commonly used examinations identified from the Delphi technique investigation.

4.2 Identification of what static based biomechanical examinations of the foot are used by podiatrists in clinical practice and the inter-assessor reliability of these examinations.

As Chapter 2 highlighted Root et al (1971, 1977) proposed a conceptual framework describing normal and abnormal foot function during walking and an assessment protocol that enables a clinician to predict the function of the foot during walking via a static (i.e. standing or non weight bearing) assessment of the foot. Understanding the reliability of an assessment protocol aims to identify whether examinations are consistent between assessors and across time (Bruton et al 2000) (when there is no change in the status of the foot). Good reliability is the basis for sound professional practice and is essential for quantifying the value of an examination (Bruton et al 2000). There is already evidence that some or all static foot assessment protocols are unreliable (Menz 1995, Menz and Keenan 1997, McPoil and Hunt 1995, Keenan 1997, Keenan and Bach 2006). However, most studies have tested only part of the assessment protocol described by Root et al (1971, 1977) and have largely adopted the examinations as they were first described (Hamill et al 1989). In reality the current implementation of the protocol for static foot assessment is influenced by many factors, including national or local professional knowledge (via discussion at workshops/conferences), clinical experience (clinicians would adapt their practice to their learning), 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). Thus, the reliability of static foot assessment protocols as they are currently used in practice has not been evaluated.

RCSP and NCSP are arguably the core elements of the Root et al (1971) static based biomechanical assessment of this foot and directly influence orthotic prescription. Their importance to practice is reflected in the fact that they have been subject to considerable scrutiny by the physical therapy and related communities (Menz 1995, Menz and Keenan 1997, McPoil and Hunt 1995, Keenan 1997, Keenan and Bach 2006, Hamill et al 1989, Pierrynowski and Smith 1996, McPoil and Cornwall 1994, McPoil and Cornwall 1996a). Menz (1995) highlighted how the assessment is prone to erroneous subjectivity due to skin movement artefact, pen marker thickness and practitioner dexterity. Menz and Keenan (1997) examined the inter-assessor reliability of a gravity angle finder to measure NCSP and RCSP. Pearson correlation coefficient values (r) (and SEM) were r = 0.367 (SEM = ±3.77°) and r = 0.742 (SEM = ±6.27°) respectively. Use of a digital goniometer did not significantly improve measurements, r values of r = 0.558 (SEM ±8.47°) and r = 0.742 (SEM = ±6.47°) respectively. Keenan and Bach (2006) report range values of -9.0° to 7.0°) for RCSP and -2.0° to 13.0° for NCSP over two measurement sessions. Both studies conclude that the large variation between assessors would affect diagnosis and treatment rationale.

Rome (1996) highlighted the difficulty of assessing the sagittal plane motion of the ankle joint. The poor alignment of the goniometer, non-identification of bony landmarks and the variation in force applied would all contribute to error (Rome 1996). Elveru et al (1988) recorded an ICC value of 0.50 and Jonson and Gross (1997) an ICC of 0.65 when examining the inter-assessor reliability of assessing ankle joint dorsiflexion with a goniometer. The greater reliability in the latter study may be due to Jonson and Gross (1997) allowing participants to maximally dorsiflex their foot rather than a clinician manipulate the foot.

The intra- and inter-assessor reliability measurement of the sagittal plane position and mobility of the first ray usually focuses on the measurement of dorsal mobility and this has been measured directly (e.g mm) and categorically (e.g classification of the range of motion or the position of the first ray). Glascoe et al (2005) reported very poor inter-assessor reliability for the direct measurement of first ray dorsal mobility using a ruler, with an ICC value of 0.05. Similarly Cornwall et al (2004) observed poor agreement and inter-assessor reliability for the classification of first ray dorsal mobility, with only 12.5% agreement for classification of first ray mobility as hypomobile and 25.0% agreement for hypermobile.

There are two approaches to limb length examination: direct measures (e.g tape measure), (Brady et al 2003, Beattie et al 1990) and in-direct methods such as palpation of bony pelvic landmarks and placing blocks under the heel of the participant (Woerman and Binder-Macleod 1984). The latter appear to have greater reliability (Woerman and Binder-Macleod 1984). Woerman and Binder-Macleod (1984) recorded small mean differences (less than 4.3mm) across five assessors when palpating the iliac crest and placing small blocks under the heel of the participant to measure the differences in limb length. Jonson and Gross (1997) recorded good inter-assessor reliability (ICC = 0.70) when placing blocks under the heel and using a levelling device to ascertain pelvis obliquity.

Understanding how foot biomechanics are assessed in current practice, and the reliability of the assessments, enables us to understand: (i) whether current practices have changed since Root et al (1971, 1977) first introduced their work; and (ii) the credibility of the assessment protocols used in current practice. This project aimed to: (Part 1) identify (through consensus) what biomechanical examinations are used in clinical practice and (Part 2) evaluate the inter-assessor reliability of a subset of these assessments.

4.2.1 Method

Part 1: Identification of a protocol for conducting a biomechanical assessment of the foot

Twelve podiatrists (working in state funded and private health care settings, six male, mean age 42) specialising in foot and ankle biomechanics were invited to participate. All worked within a specialist biomechanics/musculoskeletal clinic and had at least 3 years clinical experience at this specialist level. Ethical approval was granted (University of Salford Institutional Committee) and all participants gave written consent. A Delphi method (Grisham 2009) was chosen to derive consensus on a foot biomechanics assessment protocol. The Delphi method (Grisham 2009) is a systematic and structured examination technique involving a panel of experts. The method combines use of questionnaires and group discussion to derive consensus (Grisham 2009).

There were three keys phases to the development of a consensus.

Phase 1: Questionnaire. All podiatrists answered a questionnaire (Appendix 1.1) anonymously and without discussion. The questionnaire (written by the Principal Investigator and PB) investigated the use of static foot, leg and lower limb biomechanical examinations and gait analysis protocols by each podiatrist. Questions were derived from Root et al (1971), current undergraduate syllabus, information from Valmassey (1995) and Michaud (1997). There was also space provided for podiatrists to report any additional examinations used.

Most questions required Yes/No answers and required information on how often each examination was used, the method and whether the information was used to classify foot type and/or to develop a treatment rationale.

Phase 2: Development of draft consensus from results of the questionnaire. From the completed questionnaires, PB and HJ identified where there was both agreement and disagreement amongst the expert panel. Agreement existed when there was an identifiable trend amongst podiatrists, for example the majority of podiatrists used the same measurement technique. Disagreement was where there was poor consensus between podiatrists, for example less than half used a particular examination. A separate adjudicator (CN) was present throughout. A draft assessment protocol was developed based on the questionnaire responses.

Phase 3: Group discussion. A group discussion (led by PB, Principal Investigator took notes) explored the validity of the questionnaire results and draft foot assessment protocol from Phase 2. Discussion orientated around whether it was true reflection of the current practice of the panel members but also related professional disciplines. The areas of agreement and disagreement from the questionnaire results were elaborated upon though open discussion. Podiatrists explained in more detail their assessment methodology, their conceptual understanding of the normative basis to which pathological cases are compared and the rationale for their assessment plan.

Part 2: Evaluation of the inter-assessor reliability of the biomechanical assessment protocol

Eleven podiatrists (working in state funded and private health care settings, six male, mean age 46) specialising in foot and ankle biomechanics practice volunteered to participate. All worked within a specialist biomechanics/musculoskeletal clinic and had at least 5 years clinical experience at this specialist level.

Each podiatrist assessed six asymptomatic participants (three male, mean age 25, mean body mass index (BMI) 23), using a subset of the assessment protocol defined in Part 1 of the study. Ethical approval was granted from the University of Salford Institutional Committee and all participants gave written consent. This investigation was conducted nine months after Part 1.

Four of the eight biomechanical examination procedures identified in Part 1 were selected for the inter-assessor reliability study. These were selected primarily because the podiatrists identified them as essential rather than optional components of their clinical assessment. However, they also provided some assessment of the lower limb as well as the foot and could be completed within a reasonable time frame. The four assessments selected by podiatrists were used for all or the majority of patients and provided information critical to the development of a treatment rationale and orthotic prescription. Thus the four selected contributed more to clinical practice than the four assessments omitted.

The assessments used in the inter-assessor study were 1) NCSP and RCSP, 2) range of dorsiflexion at the ankle joint, 3) Position and mobility of the first ray, and 4) Examination of limb length. They were assessed quantitatively or qualitatively according to the preferences identified in Part 1. To help maintain consistency in how the 11 podiatrists implemented the assessment protocol, an information sheet and demonstration was provided. The participants whose feet were to be assessed were placed in six separate cubicles at the university clinic. Assessments were conducted as per the protocols described in Table 4.2 which were derived from the conclusions of Phase 1 in Table 4.1. Podiatrists were allocated 30 minutes to assess each participant and at least 30 minutes rest between each assessment. In accordance with clinical practice, each assessment was completed once for each foot. Each podiatrist recorded their measurments in a booklet. No discussion was allowed between podiatrists or participants during the assessments. All pen marker lines on the participants were removed between podiatrists.

Statistical analysis

The researchers were blind to the data in each booklet. All data was collated into Microsoft Excel and then processed through Statistical Package Social Science Software (Version 17.0) (SPSS, Chicago, Illinois, USA). The mean, range, standard deviation (SD) and 95% confidence intervals (95% CI) were calculated for NCSP, RCSP and the range of dorsiflexion at the ankle joint.

Inter-assessor reliability for RCSP, NCSP and the range of dorsiflexion at the ankle joint were calculated using ICC (2,1) in accordance with Rankin and Stokes (1998). ICC values were chosen as they assess the consistency of quantitative measurements made by multiple testers (clinicians) measuring the same objects (participants) (Bruton et al 2000). Bruton et al (2000) suggest that ICC values should not be interpreted clinically in isolation. Therefore a random effects ANOVA (analysis of variance, crossed random effects model) (Baltagi et al 2006) was used to enable further evaluation of reliability. A random effects ANOVA models y as a constant, plus a random effect due to the assessor (clinician), a random effect due to the participant (e.g moved their feet) and an overall random error of the examination itself. (E^1 assessor error, E^2 participant error, E random error).

$y = \mu + \sqrt{E^1+E^2+E}$

This calculates the extent of between participant variability, between assessor variability and the amount of random error in the examination. This provides an indication of where the majority of error occurs. Therefore for each part of the assessment (e.g. NCSP, RCSP), the error variables have to be accounted for in addition to the true value of the feature being assessed:

Value provided by the assessor = actual value + (assessor error (E^1) + participant error (E^2) + random error (E))

A particular advantage of the random effects ANOVA is that the outcomes are expressed in the same units as the measurement and thus are easily interpreted in terms of clinical practice. In addition, the three sources of error can be combined to provide an indication of the total error due to participant, assessor and random error:

$$\text{Total error} = \sqrt{(\text{assessor error } (E^1) + \text{participant error } (E^2) + \text{random error } (E)}$$

The assessment of the position and mobility of the first ray and limb length involved categorical data, therefore the percentage agreement (%) (Hunt 1986) and a Fleiss Kappa (Viera and Garrett 2005, Landis and Koch 1977) were chosen.

Percentage agreement can lack sensitivity as it does not adjust for that agreement occurring by chance (Hunt 1986). A Fleiss Kappa calculates the reliability of agreement between a fixed number of assessors (Viera and Garrett 2005, Landis and Koch 1977, Sim and Wright 2005) and is a better representation of true inter-assessor reliability (Hunt 1986). Fleiss Kappa values range from <0 for poor agreement to 1.00 for perfect agreement (Viera and Garrett 2005, Sim and Wright 2005). Both of these statistical measures are consistent with the available literature (Glascoe et al 2005, Cornwall et al 2004).

4.2.2 Results

Part 1

Tables 4.1 and 4.2 present the results of the questionnaire and the group discussion. Three key trends were derived from the questionnaire (Phases 1 and 2) and formed the basis to the subsequent discussion (Phase 3). These were:

(i) The main basis to biomechanical assessment of the foot and ankle is the description provided by Root et al (1971, 1977).

(ii) Podiatrists “estimate” rather than measure foot or limb position and motion.

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

The biomechanical assessment protocol identified through consensus comprised the following:

- Examination of the foot in NCSP and RCSP
- Examination of the range of dorsiflexion at the ankle joint
- Examination of the range of frontal plane motion at the subtalar joint
- Examination of the position and mobility of the first ray
- Examination of forefoot to rearfoot relationship in the frontal plane
- Examination of the range of dorsiflexion at the first metatarsophalangeal joint
- Examination of limb length
- Visual gait analysis

Table 4.1 presents the results of Phase 1, 2 (questionnaires) and 3 (group discussion).

Biomechanical examination	**No. of podiatrists that use the assessment (total =12)**	**Key features of examination (derived from questionnaire)**	**Consensus from group discussion**
NCSP and RCSP	9	Position is estimated not measured 9/9 Use this as an assessment of foot type 8/9 Use this to develop a treatment rationale (for example orthotic prescription)	Frontal plane position of the calcaneus relative to the leg was always observed Foot type is classified as pronated/ supinated/neutral This is a key biomechanical examination of the foot Podiatrists feel that they could accurately measure the frontal plane position of the calcaneus quantitatively if required
Range of dorsiflexion at the ankle joint	12	Range of motion is estimated, not measured 12/12 podiatrists assessed with the knee extended 9/12 podiatrists assessed with the knee flexed The total range of motion and range of dorsiflexion are measured	Podiatrists state that the normal range of dorsiflexion at the ankle joint is 10° Assessment of the range of motion is commonly based on the podiatrist's own experience as to what they perceive as normal and not through the use of a goniometer/other measuring device Podiatrists feel that they could accurately measure the range of ankle joint dorsiflexion quantitatively if required
Range of frontal motion at the subtalar joint	11	Motion is estimated not measured Subtalar joint neutral (non weight-bearing) is used as a reference position to determine the amount of pronation and supination	Podiatrists believe that this examination is a good indicator of dynamic foot function, but it is difficult to conduct
Position and mobility of the first ray	11	Position and mobility are estimated not measured 9/12 use categorical rather than numerical data	Consensus from podiatrists was that for examination of first ray mobility and position categorical data (e.g. “rigid/flexible/normal”) is more useful than numerical data Podiatrists did not measure dorsal mobility

Forefoot to rearfoot relationship	11	Position is estimated not measured. 11/11 use this assessment in the frontal plane only	No consensus on what should be used to define the forefoot (e.g. use middle three metatarsals or use all five metatarsals)
Range of motion at the first MTPJ	11	Motion is estimated not measured 9/12 assess the total range of motion of the first MTPJ 6/12 assess the range of first MTPJ dorsiflexion	Consensus from podiatrists was that assessment of the forefoot was dependent on the presenting musculoskeletal complaint/injury and their focus was always on the function of the rearfoot
Foot Posture Index (FPI) (Redmond et al 2006)	6	6/12 use the FPI as an assessment of foot type/posture	Some podiatrists were unaware of the FPI Some podiatrists did use individual elements of FPI
Assessment of the lower limb	12	All podiatrists assess the lower limb, leg and foot	Podiatrists state that it is important to assess the pelvis, lower limb, leg and foot in a biomechanical assessment
Examination of limb length	7 to 9	Limb length is estimated not measured 9/12 assess anatomical limb length 7/12 assess functional limb length	Consensus from podiatrists was that the examination of limb length is important and a limb length discrepancy is a common cause of abnormal biomechanical function of the lower limb Podiatrists feel that the process of obtaining a precise measurement (through tape measure) is not reliable and instead the leg length discrepancy should be categorised. Measurement of limb length should also involve shoulder tilt, ASIS symmetry (supine and standing)
Additional biomechanical examinations	NA	Examination of internal and external hip rotation Examination of hamstring flexibility (Straight leg raise test) "Heel raise" test to assess function of tibialis posterior	Podiatrists state that these are not mandatory examinations and therefore are only used for specific clinical presentations

Gait Analysis	11	11/11 assess the dynamic function of the foot, ankle and knee 10/11 assess the dynamic function of the hip and upper body	Dynamic assessment is as important as static examination for diagnosis and development of a treatment plan
Key determinants of the gait cycle to be observed during a routine gait analysis	NA	Position of foot at initial heel contact Forefoot and midfoot position during loading phase. Foot position and motion during propulsion and re-supination Movement of the foot and leg during swing phase Motion of the hip and knee Timing and magnitude of motion 4 to 6/12 podiatrists had access to gait analysis equipment e.g pressure plate, 2D video analysis	Podiatrists state that they follow a relatively consistent protocol when conducting a clinical gait analysis assessment. The protocol involved identifying foot function at key events during the gait cycle and always aiming to analyse these from a visual perspective. Consensus among podiatrists was that they would compare the dynamic function of a patient's foot and ankle to the description of "normal" they were taught at undergraduate level, the predominant basis for this was Root et al (1971, 1977). The consensus among podiatrists was that additional gait analysis equipment did not aid their assessment or treatment plan. All podiatrists felt they were confident in their visual analysis of the patient walking and what was feasible within the time constraints.

Table 4.2 presents the protocol used by podiatrists in current practice (identified from Phase 1, 2 and 3) for conducting each examination in the assessment protocol

Biomechanical Examination	**Method**
NCSP and RCSP	(i) Participant standing (ii) Position both feet into NCSP (iii) Pen marker bisection line drawn onto the posterior aspect of the calcaneus on both feet (iv) Measurement recorded using digital biometer for right foot (v) Identify if calcaneus is positioned varus or valgus (vi) Repeat procedure with left foot (vii)Both feet resume RCSP, measurement of the bisection line using a digital biometer for both feet
Range of dorsiflexion at the ankle joint	(i) Participant supine and sitting with back straight against plinth (ii) Position the subtalar joint into a neutral position (iii) A straight reference line is drawn onto the lateral aspect of leg indicating where one of the tractograph arms should be positioned (iv) Tractograph is positioned with one lever arm running parallel to the lateral aspect of leg and the other positioned parallel to the plantar aspect of the foot running distally (v) With the knee joint extended, the foot is maximally dorsiflexed and the measurement on the tractograph recorded (vi) The knee joint is held in a flexed position, the ankle joint is maximally dorsiflexed and the measurement on the tractograph recorded (vii) Repeat procedure with other foot

Range of dorsiflexion at the first MTPJ	(i) Participant supine and sitting with back straight against plinth with legs extended in front (ii) Place arms of the goniometer parallel to the long axis of the first metatarsal and the proximal phalanx of the hallux (iii) Manually dorsiflex first metatarsophalangeal joint with first ray free to move and measure range of motion with goniometer (iv) Repeat procedure with left foot
Forefoot to rearfoot relationship (frontal plane)	(i) Participant prone, lying down (ii) Raise one side of pelvis from couch with a cushion/pillow, so that the long axis of the contra lateral foot is vertical (iii) Position the subtalar joint into a neutral position (iv) Visually observe position of forefoot relative to rearfoot. Categorise if neutral/ everted (forefoor valgus)/inverted (forefoot varus). (v) Repeat procedure with other foot
Sagittal plane position and mobility of the first ray	(i) Participant supine and sitting with back straight against plinth (ii) Position the subtalar joint into a neutral position and the midtarsal joint is locked (pronated around both axes) through pressure applied by the thumb of one hand under the fourth and fifth metatarsal heads. (iii) The first metatarsal head is held between the thumb and the first finger in the resting position and the lesser metatarsal heads are held between the thumb holding the 4th and 5th metatarsal heads and fingers placed dorsally over them. (ii) The position of the first ray is classified (dorsiflexed/ plantarflexed or neutral) (iii) The mobility of the first ray is classified (flexible/rigid/normal) (iv) Repeat procedure with other foot
Examination of limb length	(i) Participant standing in RCSP (ii) Both ASIS are palpated, identification of whether a limb length discrepancy is present (iii) Classification of which leg is longer and whether this is less than 5mm, more than 5mm or more than 10mm (iv) Participant supine (v) Both ASIS are palpated, identification of whether a limb length discrepancy is present (iii) Classification of which leg is longer and whether this is less than 5mm, more than 5mm or more than 10mm
Visual gait analysis	On conducting a clinical gait analysis assessment the key determinants to be observed are: (i) Position of foot at initial heel contact (ii) Forefoot and midfoot position during loading phase. (iii) Foot position and motion during propulsion and re-supination (iv) Movement of the foot and leg during swing phase (v) Motion of the hip and knee (vi) Timing and magnitude of motion

MTPJ: metatarsophalangeal joint.

Part 2

The results indicate poor inter-assessor reliability for the four examinations. Table 4.3 displays the reliability results for RCSP and NCSP. For RCSP an ICC = 0.23 (right), ICC = 0.14 (left) and for NCSP ICC = 0.14 (right) and ICC = 0.11 (left) suggest poor inter-assessor reliability. All mean 95% CI were above 3.7° and the mean range of NCSP and RCSP values were greater than 8.8° (Table 4.4). The results of the random effects ANOVA indicate that the greatest error was random error (up to 4.9°), while the assessor error was up to 3.4° (Table 4.4).

Table 4.3 demonstrates ICC values for the examination of the range of dorsiflexion at the ankle joint. There was moderate agreement with ICC = 0.44 (right) and ICC = 0.42 (left) for knee extended and ICC = 0.61 (right) and ICC = 0.51 (left) for knee flexed. All mean 95% CI were above 9.0°, and the mean range of dorsiflexion at the ankle joint values were greater than 20.5° (Table 4.5). The results of the random effects ANOVA indicate that there were comparable contributions from the three sources of error, with values ranging from 4.3° to 5.8° (Table 4.5).

The results for classification of first ray position and mobility are displayed in Table 4.3. There was greater consistency for the categorisation of mobility compared to first ray position. Fleiss Kappa values of -0.03 (right) and 0.01 (left) for categorisation of position and 0.05 (right) and -0.01 (left) for the mobility of the first ray (0.05 (right) and -0.01 (left)).

Table 4.3 demonstrates the results for examination of limb length. There was less agreement on the size of the difference in limb length than the identification of the longer limb when evaluating the percentage agreement values, however results were comparable according to Fleiss Kappa values (0.02 for both longer leg and the difference in leg length). Clinicians consistently reported differences in limb length of 5mm or less (Table 4.7).

ICC values for RCSP and NCSP		
	RCSP	NCSP
Right foot	0.23	0.14
Left foot	0.14	0.11
ICC values for the range of dorsiflexion at the ankle joint		
	Knee extended	Knee flexed
Right foot	0.44	0.61
Left foot	0.42	0.51
Fleiss Kappa values for examination of the position and mobility of the first ray		
	First ray position	First ray mobility
Right foot	-0.03	0.05
Left foot	0.01	-0.01
Fleiss Kappa values for the examination of limb length		
	Identification of longer leg	Identification of longer leg length
Examination of limb length	0.02	0.02

Table 4.3 - Inter-assessor reliability results for all examinations

Foot	Examination	Mean (°)	SD (°)	Range (°)	95% CI (°)
Right foot	RCSP	0.2	3.2	11.2	-2.0 to 2.6
	NCSP	3.4	3.6	12.2	0.9 to 5.8
Left foot	RCSP	-0.4	3.4	11.2	-2.7 to 1.9
	NCSP	3.2	2.8	8.8	1.2 to 4.9
Results of random effects ANOVA					
		√Estimate of covariance parameter (°)			
Foot	**Examination**	**√E random error (°)**	**√E¹ assessor error (°)**	**√E² subject error (°)**	**Total (°)**
Right foot	RCSP	3.2	0.6	1.8	3.8
	NCSP	2.2	2.9	0.8	3.8
Left foot	RCSP	4.9	3.4	1.1	9.5
	NCSP	2.2	1.8	1.0	3.1

Table 4.4 - Descriptive analysis of the variation between assessors in the examination of RCSP and NCSP

Foot	Examination	Mean (°)	SD (°)	Range (°)	95% CI (°)
Right foot	Knee extended	3.9	7.0	23.0	-0.8 to 8.6
	Knee flexed	10.5	7.3	23.0	5.6 to 15.5
Left foot	Knee extended	3.0	6.6	20.5	0.1 to 9.1
	Knee flexed	7.5	6.9	22.2	5.2 to 14.2
Results of random effects ANOVA					
		√Estimate of covariance parameter (°)			
Foot	Examination	**√E random error (°)**	**√E¹ assessor error (°)**	**√E² subject error (°)**	**Total error (°)**
Right foot	Knee extended	5.2	4.9	4.6	10.7
	Knee flexed	4.5	5.8	5.7	9.3
Left foot	Knee extended	4.9	4.6	4.3	8.0
	Knee flexed	5.1	4.9	5.2	8.7

Table 4.5 - Descriptive analysis of the variation between assessors in the examination of the range of ankle joint dorsiflexion

Percentage agreement values				
Foot	Examination	**Plantarflexed (%)**	**Neutral (%)**	**Dorsiflexed (%)**
Right foot	First ray position	55.0	31.5	13.5
Left foot		62.0	30.0	8.0
		Flexible (%)	**Neutral (%)**	**Rigid (%)**
Right foot	First ray mobility	94.0	1.5	4.5
Left foot		91.0	7.0	2.0

Table 4.6 - Descriptive analysis of the variation between assessors in the categorisation of the position and mobility of the first ray

Percentage agreement values				
Examination	**Right (%)**		**Left (%)**	**None (%)**
Identification of longer leg	64.0		12.0	24.0
	up to 5mm(%)	**5-10mm (%)**	**greater than 10mm (%)**	**None (%)**
Identification of longer leg length	23.0	39.0	14.0	24.0

Table 4.7 - Descriptive analysis of the variation between assessors for the categorisation of the longer limb and the difference in limb length

4.2.3 Discussion

Biomechanical assessment protocol that podiatrists use in clinical practice

The assessment protocol developed in Part 1 of this investigation is largely a modified version of Root et al (1971, 1977). The description provided by Root et al (1971, 1977) is still very much at the forefront of the biomechanical clinical assessment of foot biomechanics and the basis for clinical descriptors of foot function during gait. This demonstrates the continued influence of Root et al (1971, 1977) and the strong effect undergraduate education has on subsequent practice. No podiatrist measured the dorsal mobility of the first ray even though there is a significant amount of literature evidence describing the assessment, of those who did examine the first ray, they chose to assess the position and mobility of the first ray following the Root et al (1971) protocol. Only some used the Foot Posture Index (Redmond et al 2006) which suggests that although many (Redmond et al 2006, Barton et al 2011, Teyhen et al 2012, Evans et al 2003, Sanchez-Rodriguez et al 2012, Muntenau and Bassed et al 2006, Chuter et al 2010, Nielson et al 2008) have described the advantages and disadvantages of the Foot Posture Index and used it as a classification measure of the normal or abnormal foot it has not yet become an examination of the foot routinely used by podiatrists in clinical practice as for example the examinations described by Root et al (1971, 1977) are regarded. However, the inclusion of a visual gait assessment signifies that podiatrists have adopted new assessment approaches that they deem to add value. This did not extend as far as the use of potentially valuable instrumented gait assessment methods (For example video analysis, pressure plate).

Contrary to the specific instructions of Root et al (1971, 1977), podiatrists choose to estimate and classify joint position/motion rather than ascertain a directly measured numerical value. For example, when assessing the ankle joint, podiatrists choose to estimate the range of dorsiflexion rather than use a goniometer. Podiatrists felt that their experience was sufficient to accurately classify the range of motion as normal, flexible or rigid. All podiatrists stated that they were confident this approach was valid and cited time constraints as the primary barrier to use of objective measures. However, continuing to use assessments that have been shown to have low reliability is likely to be considered unsound practice. If reliability could be improved by an objective rather than subjective assessment, even if it takes longer to complete, then this could form a strong case to extend the time available for the assessment of patients.

These differentiations from the original description and instructions of Root et al (1971, 1977) justify the consensus exercise in Part 1 and ensure that our investigation of inter-assessor reliability is relevant to current clinical practice.

Inter-assessor reliability of the biomechanical assessment protocol

There was poor inter-assessor reliability recorded for all of the static biomechanical examinations of the foot, leg and lower limb which questions their value in clinical practice. RCSP and NCSP produced poor inter-assessor reliability results (all ICC values were less than 0.23), and this concurs with the available literature. Picciano et al (1993) recorded ICC values for NCSP of 0.15 and 95% confidence intervals of 0.87° to 8.65°. The results of the random effects ANOVA suggest that for RCSP and NCSP random error is the key issue. Differences between assessors of this scale would create different treatment plans and orthotic designs. Both Menz (1995) and Elveru et al (1988) highlight that an overwhelming priority is placed upon the outcomes of these measurements in clinical assessment and orthotic prescription. However, the poor reliability and large variation in the results recorded here and elsewhere (Menz 1995, Menz and Keenan 1997, Keenan and Bach 2006, Eleveru et al 1988) should be clinically unacceptable and we therefore question their continued use in clinical practice (Menz 1995, Eleveru et al 1988).

Although podiatrists reported some difficulty in using the goniometer (Rome 1996), moderate reliability was observed for the examination of the range of ankle joint dorsiflexion at the ankle joint. Elveru et al (1988) and Jonson and Gross (1997) report similar ICC values of 0.50 and 0.65. In Part 1 of this study all podiatrists stated that they believed the examination of range of dorsiflexion at the ankle joint provided a good indication of dynamic foot function. However, the low reliability and large range of values recorded across assessors questions the clinical value of these examinations. Considering that 10° of dorsiflexion was stated as normal (results from Part 1, Table 4.1 based on Root et al (1971), Table 4.3), clinical measures at either boundary of the 95% CI (maximum 95% CI were 5.6° to 15.5°)

and the total error of up to 10.7°, could lead to false identification of the range of dorsiflexion at the ankle joint. This would directly affect the treatment rationale if the outcome suggested limited or adequate range of ankle joint motion. Moseley and Adams (1991) suggest that such variation would make measurement of changes in the range of motion due to interventions (e.g. stretching) unreliable. The results from the random effects ANOVA suggest that all three sources of error contribute to variation between assessors. Since random error was quite large (5.2°, left foot, knee flexed), reducing errors from participants and assessors (e.g through training, use of measurement tools) still might not achieve an acceptable level of reliability.

Classification of first ray mobility demonstrated greater reliability than categorisation of first ray position. The Fleiss Kappa values of less than 0.05 for categorisation of first ray position and mobility indicate only poor to slight agreement (Viera and Garrett 2005, Landis and Koch 1977). For four of the 12 feet assessed there was greater than 90% agreement for classification of first ray range of motion as flexible. However, percentage agreement can lack sensitivity as to the true level of agreement between assessors as it can over or under estimate the actual level of agreement and does not account for the possibility that the agreement observed occurred by chance (Hunt 1986). High levels of agreement for assessment of flexibility might be expected as 'rigidity' suggests no motion at all and this is more easily identified than different grades of "some" motion (Michaud 1997). However, taking into account the Fleiss Kappa and percentage agreement statistical values only poor to moderate reliability was observed. Classification of first ray position demonstrated poor agreement between assessors. There are significant identifiable differences between a plantarflexed and dorsiflexed first ray (Michaud 1997), something that experienced podiatrists would expect themselves to be able to identify. As with measures of rearfoot alignment, first ray position can influence orthotic prescription (Michaud 1997).

Identification of the longer limb provided marginally better agreement than classifying the actual amount of leg length difference, but still only suggests slight agreement (Viera and Garrett 2005, Landis and Koch 1977) with Fleiss Kappa values of 0.02 (longer leg) and 0.02 (difference in leg length). This level of reliability is similar to Woerman and Binder-Macleod (1984). To be able to ascertain that there is a difference in limb length of less than 5mm requires high precision and it is doubtful that through visual inspection and palpation a clinician could reliably work to such accuracy. If a clinician can identify a discrepancy this small then they will almost always identify a limb length difference because the skeleton is rarely truly symmetrical.

4.2.4 Clinical Implications

One purpose of clinical assessment is to decipher normal from pathological (Jonson and Gross 1997, Lorimer et al 2002, Valmassey 1995, Michaud 1997) but the results from this investigation suggest that it would not be possible to accurately classify either. The protocol described by Root et al (1971, 1977) states precise measurements are required when undertaking a static biomechanical assessment of the foot. Results from this and prior research (Keenan 1997, Keenan and Bach 2006, Elveru et al 1988, Menz and Keenan 1997, Picciano et al 1993) suggest that such accuracy is not achieved in clinical practice. For example, Root et al (1971, 1977) states that RCSP and NCSP measurements will precisely dictate the inclination of a rearfoot wedge used in a foot orthoses. However the variability in the assessment of rearfoot position reported here would lead to very different orthotic prescriptions. This directly undermines the biomechanical rationale for intricate adjustments in the design of foot orthoses and the capture of static foot shape as a basis for foot orthosis design. This has profound implications for many areas of clinical practice and suggests a reappraisal of the theoretical and practical basis for orthotic practice is warranted. The low reliability of the assessments evaluated here questions their ability to accurately infer the behaviour of the foot during stance, which is the purpose of the static assessments in the model proposed by Root et al (1977). The results here also add weight to the case for a move toward objective assessment of dynamic foot behaviour in clinical practice, regardless of the practical challenges this raises.

4.2.5 Limitations

There are several limitations to this preliminary investigation reported here. Four of the eight examinations used by assessors (from Part 1) were not included in Part 2 of this study. They were excluded because the podiatrists identified them as 'optional'. Other clinicians might disagree, especially if their practice is different to that of the podiatrists involved in this current study. Using all eight examinations would have been logistically difficult with the number of assessors and participants in this study and time available for the assessments. The number of assessors used was relatively small and might not represent the true variation across the entire professional communities using the assessments evaluated in this work. All were podiatrists and whilst their professional networks are strongly multi-professional, practices could differ in other disciplines and countries. The literature indicates that the measures used by the assessors and those evaluated in the reliability study, are also used in the physical therapy profession (Jonson and Gross 1997, Elveru et al 1988, Beattie et al 1990). The development of the foot assessment protocol occurred through just one iteration of the Delphi method, whereas two or more iterations are often employed (Grisham 2009). Experience during the exercise suggested that consensus was already in place or very close from the outset. The number of feet assessed was quite small and all participants were free from pathology. The participants were young with an average BMI and may not represent feet that present in many clinical cases. Arguably, assessing these feet is easier than those of people in pain, feet with deformity or in cases of greater BMI, and thus our results might reflect a "best case" scenario in terms of reliability. This study recorded low ICC values, in particular for NCSP and RCSP. The large number of assessors and small number of participants would have increased the variability and therefore could have decreased the inter-assessor reliability. Finally, good reliability does not infer practical usefulness of the assessment. Good reliability may simply reflect low sensitivity and specificity in the measure, or highly repeatable errors by assessors. Thus, good reliability does not infer validity. However, measures cannot be valid unless reliable, and outcomes of this work indicate many of the assessments used in foot health practice are unreliable and thus invalid.

4.2.6 Conclusion

This preliminary investigation identified through consensus what biomechanical examinations of the foot are used by podiatrists in current clinical practice and the predominant basis to this is the descriptions by Root et al (1971, 1977). However the key examinations used to predict the function of the foot during the gait cycle, to construct a treatment plan and to determine orthotic prescription are unreliable.

CHAPTER FIVE – METHODS

5.1 Overview

Chapter 5 describes the methods used in this investigation for the collection and analysis of data. It describes the process used for the recruitment, and determination of suitability of participants for inclusion into this investigation. The protocol used for the static based biomechanical assessment of the foot for Data Set A is explained. This details how the measurements obtained were used to classify feet with, or without a structural deformity following the guidelines from Root et al (1971, 1977). For the collection of Data Set B, there is a description of the equipment and the design of the foot model used for the collection of three dimensional co-ordinate kinematic data. All processing and analysis of data within all of the software used is described. All statistical analysis conducted to present the required data is described.

5.2 Subject selection

This investigation was approved by institutional review from the University of Salford prior to the recruitment of any participants (Ethical Approval Code: RGEC08/090).

There were three key objectives when recruiting participants for this investigation: a. All participants must be asymptomatic, b. To recruit a large cohort of participants (more than n=100), and c. Recruitment of both male and female participants.

Recruitment of participants for this investigation

To recruit participants the Principal Investigator provided a short presentation to undergraduate podiatry students, and posters were displayed around the University of Salford campus explaining the initial inclusion criteria. The inclusion criteria stated that all suitable participants for this investigation must be aged between 18-45 years, and perceive that they are asymptomatic. A more in-depth screening assessment of each participant was conducted after recruitment, and is explained later.

The age range of between 18-45 years was specified because Kumar and Clark (2005) stated that individuals younger than 18 may still be undergoing physiological and skeletal maturity. Individuals older than 45 may be at a greater risk of developing systemic health conditions, such as type 2 diabetes, coronary vascular disease and osteoarthritis. Lorimer et al (2002) described how these complications can cause structural changes to the musculoskeletal, skin and vascular systems of the foot. For example, Nigg et al (1992) and Joseph (1954) reported that the range of motion at the subtalar and ankle joint (Nigg et al 1992), and first metatarsophalangeal joint (Joseph 1954) reduced considerably with increased age.

A total of 140 participants were recruited. Each was assigned a date for attendance to the podiatry gait laboratory for the screening assessment, and prospective data collection.

5.2.1 Data Collection protocol

The data collection process was split into three phases and the experimental protocol for each phase was explained to the participant before the commencement of Phase 1.

Phase1: Screening of participants to determine if they are asymptomatic

Phase 2: Data set A: Anthropometric data from a static based biomechanical assessment of the foot

Phase 3: Data set B: Instrumented gait analysis of the foot and leg

Only if the participant was classified as asymptomatic from the screening assessment in Phase 1 were Phase 2 and Phase 3 of data collection commenced.

Between 4, to 6 participants were screened per day. On the same day both Data set A and Data set B were collected. All data collected from the three phases was stored anonymously as each participant was assigned a participant number, and could not be identified from the data collected in Data set A and Data set B.

5.2.2 Phase 1 screening assessment protocol

For the purpose of this investigation, and to be able to provide suitable conclusions to Research Question 1 and 2 it was necessary to collect data from “normal” participants. For this investigation and as used in the majority of contemporary research (For example: Leardini et al 2007, Cornwall and McPoil 1999a, Hunt et al 2001a, Jenkyn and Nicol 2007, Lundgren et al 2007) the term “asymptomatic” which is described as *free of symptoms or not causing symptoms"* (Youngson 2004) was used to classify participants as "normal."

All participants were assessed using a specifically designed screening assessment protocol. This was conducted prior to the commencement of Phase 2 and Phase 3. The screening assessment protocol followed guidelines by Lorimer et al (2002) and Yates (2012). They suggested that the assessment of a patient should include the medical history of the patient, as well as an examination of the musculoskeletal, vascular and neurological systems of the foot, leg and lower limb. Any participants who did not meet the inclusion criteria, and were therefore classified as symptomatic were excluded from this investigation. No further data collected from them.

The screening assessment protocol of all participants was conducted by the Principal Investigator. Both feet were assessed as Data set A and Data set B were to be collected from both feet. The screening assessment included:

General participant information

The weight and the height of the participant were measured and recorded to enable the calculation of the Body Mass Index (BMI). The BMI was calculated using the NHS BMI online calculator (NHS 2012) for each participant. The inclusion criteria for the BMI classification of a participant in this investigation was defined from BMI: 16-29. This includes both "healthy" and "overweight" classifications. Participants were excluded from this investigation if the BMI classification was less than 16 indicating "severely underweight," or equal to and greater than 30 indicating "obese." The calculation of BMI is described by the National Institute for Health and Clinical Excellence (NICE) (2006) as a widely accepted model to determine if a patient is overweight or obese, and therefore at risk of health problems and co-morbidity.

Each participant was also asked to grade their level of activity from 0 (not active) to 5 (very active, e.g sport/go to the gym 5 or more sessions per week).

Medical history

Participants were excluded from this investigation if they had been diagnosed with an acute or chronic illness (e.g. type 1 or 2 diabetes, rheumatoid arthritis or coronary heart disease), or were taking long term medication including pain killers. Participants currently suffering from, or had previously suffered from any musculoskeletal injury, trauma or pain in the foot, leg, lower limb or lower back were excluded from this investigation. Participants who were wearing or had previously worn orthotics, even if they were now symptom free were excluded from this investigation. This is because prior to orthotic intervention the individual was not symptom free and the individual may display a different biomechanical function of the foot, leg and lower limb when walking barefoot, then when they are wearing the orthoses.

Visual assessment of the foot

Participants were excluded from this investigation if either foot displayed mild to severe structural foot deformity, such as hallux-abducto valgus, or any form of swelling or redness in the foot, leg or lower limb.

Neurological sensory assessment of the foot

A neurological assessment aims to test an individual's sensory response to different forms of stimuli (Yates 2012). The key elements of a neurological assessment according to Foster (2006) must include an examination of an individual's response to the application of pressure and vibration to the foot.

To assess the participant's response to pressure, a 10g monofilament was applied to the heel, fifth metatarsal and the hallux as explained in Yates (2012), Foster (2006) and Williams and Pickup (2005). To assess the participant's response to vibration, a 128Hz tuning fork was applied to the medial mallelous heel, fifth metatarsal and the hallux as explained in Yates (2012), Foster (2006) and Williams and Pickup (2005). Each apparatus was used separately, and each participant was required to state if they could feel the application of the apparatus and where it was applied on their foot.

Any participant unable to detect the application, or identify the location of either or both neurological assessment tools was excluded from this investigation.

Vascular assessment of the foot

A simple vascular assessment was conducted. This involved the palpation of dorsalis pedis pulse and posterior tibial pulse. Both limbs were also checked for signs of vascular disease. Participants were excluded if the Principal Investigator failed to locate either pulse, there were signs of vascular disease in either limbs or they were suffering from or had suffered from any form of acute or chronic circulatory or vascular disease or were now taking medication for a presenting condition

5.2.3 Outcome from Phase 1 screening assessment

From the 140 participants recruited, 123 participants were assessed using the screening assessment protocol, with 107 participants classified as asymptomatic from this cohort (Figure 5.1).

Participants were allocated a time on the same day of the screening assessment protocol to attend the podiatry clinic to be assessed with the assessment protocol described in Data set A, and another time to attend the podiatry gait lab for the instrumented gait analysis described in Data set B.

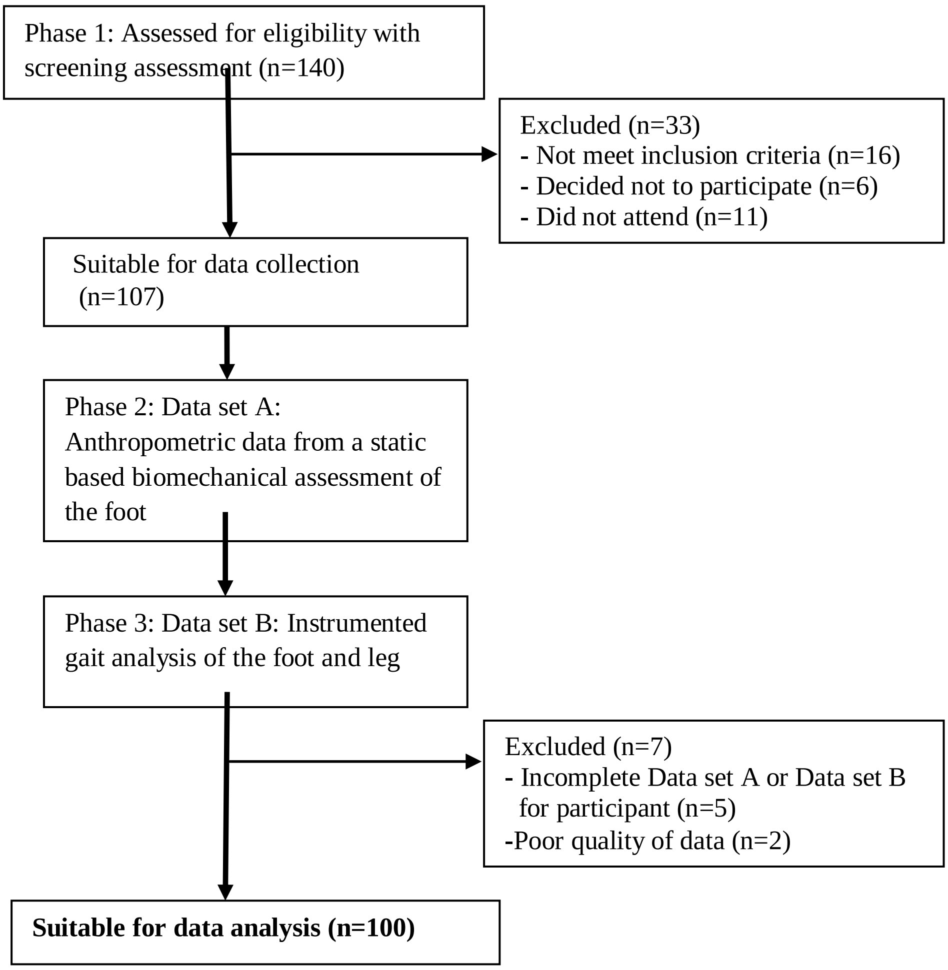


Figure 5.1 - Process of inclusion and exclusion of participants for this investigation

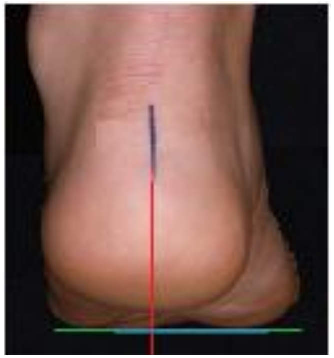
5.3 Data set A: Anthropometric data from a static based biomechanical assessment of the foot

All participants were assessed in the podiatry clinic at the University of Salford by one examiner (PB), who is an experienced podiatrist with more than thirty years clinical experience. Each examination was conducted once on both feet using exactly the same protocol for either foot. The description provided in Table 5.1 only describes the examination of one foot. All data was recorded in a specifically designed assessment Microsoft Excel spreadsheet, and all data was stored anonymously.

The measurements obtained from each examination were used to classify the foot examined as with, or without a structural deformity by following the Root et al (1971, 1977) assessment protocol.

Table 5.1 presents a step by step guide for the method of examination for each biomechanical examination of the foot, leg and lower limb used in Data set A. Included within Table 5.1 is the parameters used to classify feet from the results of each examination for this investigation.

Name of static examination	Method of examination	Photo	Foot classification parameter used for this investigation
NCSP and RCSP	i. With the participant standing in normal angle and base of gait, the long axis of the foot is viewed, ensuring that both feet are positioned in the same angle of gait. ii. Both feet are positioned in NCSP. iii. The upper and lower borders of the medial and lateral aspect of the posterior surface of the calcaneus are palpated and a midline between these is visually estimated. A point is drawn with a fine tipped felt tip pen on the upper and another on the lower aspect of this midline and a line is drawn between these points to form the bisection line. iii. A Digital Biometer™ (*) is used to measure the angle of the bisection line and was firstly zeroed to 0° when placed on a hard flat surface, e.g a table. Therefore the angle of the bisection line will be perpendicular to this and in a neutral foot should demonstrate 90°. iv. The angle of the bisection line is measured and the result classified. v. Both feet resume RCSP and the bisection line is re-measured.		Feet were classified as normal if the frontal plane angle of the calcaneus in NCSP demonstrates a neutral position (90°). Feet were classified with a rearfoot varus if the frontal plane angle of the calcaneus in NCSP demonstrates an inverted position (>90°). Feet were classified with a rearfoot valgus if the frontal plane angle of the calcaneus in NCSP demonstrates an everted position (<90°).
Examination of the range of dorsiflexion at the ankle joint	i. With the participant seated and their back straight against the plinth, both knees extended and the subtalar joint is placed into a neutral position. ii. The head of the fibula and lateral mallelous are palpated and a straight edged ruler is placed from each bony landmark along the lateral aspect of the leg. A straight reference line is drawn with a fine tipped felt tip pen on the lower third of the leg. iii. One goniometer arm of a Biometrics Ltd™ two axis flexible goniometer (**) was positioned in the centre of the reference line drawn onto the lateral aspect of the leg and the other goniometer		Feet were classified as: <10° or >10° and <15° or >15°

	arm was positioned on the lateral side of the heel. Goniometer arms were attached with double sided sticky tape. iv. Using a 90° right angled set square placed on the reference line on the lateral aspect of the leg the foot was positioned to 90° and the goniometer was zeroed to 0°. v. The foot is maximally dorsiflexed onto the leg and the measurement on the goniometer recorded.		
Examination of the range of dorsiflexion at the first MTPJ joint	i. The participant should be seated with their back straight against the plinth and both knees extended. ii. The long arm of a 6″ standard finger goniometer (***) is placed along the medial aspect of the shaft of the first metatarsal and the short arm is placed along the medial aspect of the proximal phalanx of the hallux. iii. The hallux is maximally dorsiflexed against the first metatarsal and the measurement on the goniometer is recorded. The first metatarsal head is allowed to plantarflex during this examination which should simulate the normal range of dorsiflexion at the first metatarsophalangeal joint available during propulsion. iv. Repeat examination with the other foot.		Feet were classified with <65° or >65° range of dorsiflexion.
Examination of forefoot to rearfoot relationship in the frontal plane	i. With the participant lying in a prone position one side of the pelvis is raised from the couch with a cushion, so that the long axis of the contra lateral foot is vertical. ii. The subtalar joint of the contra-lateral limb is placed into a neutral position. The upper and lower borders of the medial and lateral aspect of the posterior surface of the calcaneus are palpated and a midline between these is visually estimated. A point is drawn with a fine tipped felt tip pen on the upper and another on the lower aspect of this midline and a line is drawn between these points to form the bisection line. iii. A photograph was taken of the plantar aspect of the foot from distal (heel) to proximal (forefoot). The subtalar joint was not held in a neutral position as it was not possible to hold the subtalar joint in neutral position and take the photograph.		Feet were classified from the 2-4 metatarsal bisection line and the 1-5 metatarsal bisection line. A foot is classified with no forefoot deformity if the forefoot plantar metatarsal line demonstrates 90°. A foot is classified with a forefoot varus if the forefoot plantar metatarsal line demonstrates >90°. A foot is classified with a forefoot valgus if the forefoot plantar metatarsal line demonstrates<90°.

	Measurement of forefoot to rearfoot relationship on the photograph: i. The heel bisection line is extended from the heel in a plantar direction (red line on Image). ii. A line is drawn across the plantar surface of metatarsals 2-4 (blue line on Image) and another extends across the plantar surface of metatarsals 1-5 (green line on Image). iii. One arm of a goniometer is placed on the heel bisection line and the other goniometer arm on one of the plantar metatarsal lines. The angle of the forefoot plantar metatarsal line can now be measured from 90°.		
Examination of the sagittal plane position and the mobility of the first ray	i. The participant should be seated with their back straight against the plinth and both knees extended. ii. The subtalar joint is placed into a neutral position and the midtarsal joint is locked (pronated around both axes) through pressure applied by the thumb of one hand under the fourth and fifth metatarsal heads. iii. Adjust viewing position to look down the foot anterior to posterior, the heel should just come into view. iv. The position of the first metatarsal is classified visually. v. The first metatarsal head is held between the thumb and the first finger in the resting position of the first metatarsal, care should be taken not to plantarflex or dorsiflex the first metatarsal. vi. The lesser metatarsal heads are held between the thumb holding the 4th and 5th metatarsal heads which is repositioned to cover the plantar aspect of 2-5 metatarsal heads and the fingers placed over the dorsal aspect of the foot. Both thumbs are placed parallel to each other. vii. The resting position of the first ray is classified. viii. To assess the range and quality of motion at the first ray; It is manually dorsiflexed and the range of dorsiflexion relative to the plantar plane of 2-5 metatarsal heads is estimated. It is then manually plantarflexed and the range of plantarflexion relative to the plantar plane of 2-5 metatarsal heads is estimated.		The first ray is classified as neutral if it is in line with the position of the plantar surface of the lesser 2-4 metatarsals and demonstrates equal range of plantarflexion and dorsiflexion. The first ray is classified as plantarflexed if it is plantarflexed relative to the position of the lesser 2-4 metatarsals and displays more plantarflexion than dorsiflexion. The position of the first ray is classified as dorsiflexed if it is dorsiflexed relative to the position of the lesser 2-4 metatarsals and demonstrates more dorsiflexion than plantarflexion The mobility of the first ray is classified as: -Normal/Flexible/Rigid

<table>
<tr>
<td>Examination of limb length</td>
<td>For each examination, there were two phases:
1. Identify if there is a difference in leg length and which leg is longer.
2. Estimate the size of the difference in leg length as <5mm, 5-10mm and >10mm.

Examination 1: Sitting
i. The participant should be seated with their back straight against the plinth, knees extended and both malleoli are brought together ensuring each limb is extended equally from the midline of the body
ii. The subtalar joint and ankle joints of both feet are placed in a similar position.
iii. The flat surface of a straight edged ruler is placed parallel to the distal edge of the plinth and moved to the plantar surface of the heels. If there is no limb length discrepancy both heels will touch the ruler. If there is a limb length discrepancy the heel of the longer limb will only contact the ruler.
iv. The longer leg and an estimation of the size of the leg length discrepancy are recorded.

Examination 2: RCSP
i. The participant should be standing in RCSP, in their normal angle and base of gait.
ii. The subtalar joint and ankle of both feet are placed in a similar position. For example if one foot was more pronated then this could indicate that foot is compensating for the abnormal limb length as proposed by Root et al (1977). Therefore aligning both feet would reduce the compensation mechanism and also in relation to stage iii, it would ensure that the longer leg is identifiable as the compensation mechanism by the subtalar joint would actually lower the height of long leg ASIS.
iii. Both ASIS are palpated and if there is a difference in height of the ASIS the higher ASIS (therefore the longer leg) is recorded with an estimation of the size of leg length difference .</td>
<td> 

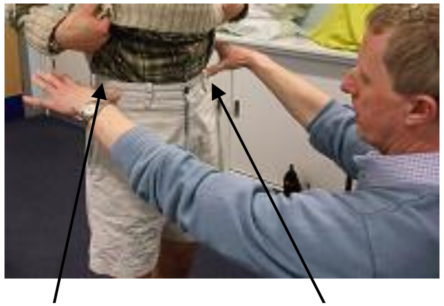

</td>
<td>The longer limb was identified and an estimation of the leg length difference of <5mm, 5-10mm and >10mm.</td>
</tr>
</table>

Table 5.1 - MTPJ: metatarsophalangeal joint. *: A Digital Biometer (www.langergrp.con/digitalbiometer-p-1189) ** A two axis flexible goniometer (Motion Lab Systems www.motion-labs.com/index.html (formerly Penny and Giles)) *** A finger goniometer (http://www.healthandcare.co.uk/range-of-motion/baseline-finger-small-joint-goniometer.html).

5.4 Data set B: Instrumented gait analysis of the foot and leg

To collect three-dimensional foot, and leg kinematic data a twelve infra-red OQUS system (Qualisys system, Qualisys, Gothenburg, Sweden) which uses passive retro-reflective markers was used. Qualisys system propriety software Qualisys Track Manager (QTM) program was used for data collection and digitisation of this data.

There are three stages to the collection of co-ordinate data when using the Qualisys system and QTM program, these are: a. Camera placement and calibration of camera system, b. Data collection and c. Data analysis.

5.4.1 Laboratory design and camera placement

The gait laboratory used is a multi-use clinically orientated laboratory. The cameras are fixed 234cm high from the gait laboratory floor, onto the wall around the edge of the gait laboratory.

This camera placement design offers ease of use, with the potential to capture a large volume of data. As the cameras are fixed to the wall it is also more suitable for some patients, (e.g children/the elderly) than the use of cameras on tri-pods. Although there are four AMTI (Type BP400600, Dimensions: 400mm x 600mm) forces plates situated in the centre of the gait laboratory, it was deemed more suitable to just use one force plate and focus the capture volume area around this. This is because of the relatively large distance from the infra-red cameras to the force plate, the small size (7mm), and the large number of the retro-reflective markers that were placed on to the foot and the effect these factors may have on the quality of the data collected.

5.4.2 Calibration of camera system

Calibration of the camera system is described by Chiari et al (2005) and Richards (2008) as an essential process for ensuring the collection of optimum data from the motion analysis system in use. Calibration defines the capture volume area. It determines the ability of the infra red cameras to ascertain a known distance, and location of specific retro-reflective markers relative to each other within the designated capture volume area.

Chiari et al (2005) described how within this capture volume area the camera system is able to determine specific internal parameters. This included the geometric, and optical characteristics of the cameras, and external parameters such as the position and orientation of the camera frame relative to the global reference frame. Using the two-dimensional images captured by the infra-red cameras of the markers placed within the capture volume area during calibration it is possible to determine the accuracy of the camera system to extrapolate three-dimensional co-ordinates from these two-dimensional images. This uses the direct linear transformation technique as described by Stevens (1997) and Abdel-Aziz and Karara (1972).

To calibrate the Qualisys system involves using an “L” frame (Figure 5.2), which has four markers placed on it of known distance, and three-dimensional location from each other. A “T” shaped wand is also used with two retro-reflective markers placed at either end (Figure 5.3). The “L” frame was placed on the right hand corner of the force plate (Figure 5.2), and each infra-red camera could see all of the markers attached to the “L” frame. The position of the “L” frame is used to determine the position of the Global Co-ordinate System, so that each camera knows where the origin of the laboratory (e.g 0,0,0) is. In this investigation the Global Co-ordinate

System was defined with x in an anterior posterior direction, y in a medial lateral direction, and z pointing upwards. The “T” shaped wand (Figure 5.3) was moved in three orthogonal planes over a specified duration of 30 seconds within the measurement capture volume.

Figure 5.2

Figure 5.3

A calibration result is recorded, and within this is the “average residual.” This was used as the main determinant of whether the calibration was successful. The average residual is a measure of how the infra-red beams from each camera are deviated from their intended direction. To measure the amount of deviation, and therefore determine the accuracy of the camera system the distance between the two markers attached to the “T” frame are measured by the infra-red cameras. The distance measured by them is then compared against the actual known distance between the markers. The higher the average residual value indicates the less accurate the camera system is at determining the actual position of a marker. According to the manufacturers guidelines (QTM_Manual2.3) the average residual should be less than 2.0mm. For this investigation the average residual for all calibrations had to below

1.0mm. If the average residual value was greater than 1.0mm the camera system was re-calibrated.

To collect three-dimensional co-ordinate data, retro-reflective markers (markers) were used. These are recorded as two dimensional images by the infra-red cameras, and then transformed by QTM program into three dimensional trajectory points. Two or more cameras must be able to visualise the position of a marker for it to be able to be re-constructed by QTM program. Reconstruction parameters such as the prediction error, and maximum residual help to estimate the position of the marker in the next frame from using the current known position of the marker in the previous frame.

Prediction error

The prediction error creates a cone like shape that extends from the current known position of the marker until it reaches the height of the specified prediction error. The aim of the prediction error is to provide a margin of error for where the three-dimensional point of the marker may deviate from where it is mathematically assumed to be in the next frame. This is demonstrated by Figure 5.14. In this figure, the red ball represents the current three-dimensional position of the marker, and with using the prediction error the blue sphere is created. The blue sphere represents the possible area of where the three dimensional position of the marker could be accepted as part of this trajectory. The black cross (+) represents the predicted position of the marker in the next frame. The prediction error for this investigation was set at the recommended default value by the manufacturer’s guidelines (QTM_Manual2.3) at 30mm.

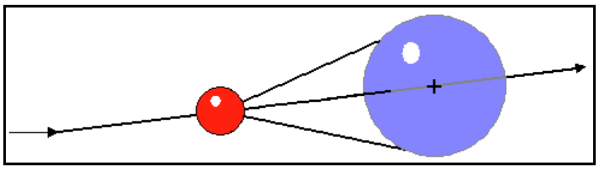


Figure 5.4 is adapted from QTM program user manual (QTM_Manual2.3)

Maximal Residual

In conjunction with the prediction error, the maximal residual can also help to estimate the position of the marker. It is the threshold level set for the maximal distance that the algorithm used to determine the accuracy of the mathematical image conversion from two-dimensional image to three-dimensional marker co-ordinate value can be estimated by the camera. A larger residual value can result in greater error by QTM program when estimating the position of the marker, but it can increase the possibility of locating the position of the marker for the next frame. The maximal residual for this investigation was set at the recommended default value by the manufacturer guidelines (QTM_Manual2.3) at 10mm

5.4.3 Retro-reflective marker set up and development of the Salford foot model

There are many advantages and disadvantages of the many skin mounted marker systems (Leardini et al 2007, MacWilliams et al 2003, Hunt et al 2001, Moseley et al 1996, Rattanaprasert et al 1999, Kitaoka et al 2006, Simon et al 2006, Carson et al 2001, Jenkyn and Nicol 2007, Nester et al 2007) described in Chapter 3, Section 3.5. In consideration of these, and the potential problematic difficulties when using skin mounted markers, it was determined that for this investigation the foot model used in Nester et al (2007) would be adopted and developed further.

The foot model used in Nester et al (2007) was the initial development of the "Salford foot model." This is different to the majority of other foot models because rigid plastic plates are designed to represent the shape of the different rigid segments of the foot. These are then attached to the dorsum of the foot, with markers placed on top of these plastic plates. The majority of foot models described in Chapter 3, Section 3.5 place markers directly onto the skin of the foot. The use of rigid plastic plates has two key advantages over the use of individual markers. First, it helps to reduce the movement of markers relative to each other within each rigid segment. This ensures that the segment being modelled is representative of "rigid," and the movement of the plastic plate relative to the skin is one movement of the whole segment, and not individual markers relative to each other. Secondly Karlsson and Tranburg (1999) reported that increasing the size of the marker can significantly decrease the marker oscillation, or vibration of the marker. Therefore, increasing the size of the marker base should have a similar effect. Angeloni et al (1993) suggested that plate mounted markers are more practical, easier to use and accurate at measuring bone movement than individual markers. This is in agreement with the results from Nester et al (2007) as discussed in Chapter 3, Section 3.5.

There were two major modifications to the model designed by Nester et al (2007). First, the medial forefoot segment was modified so that it only represented the dimensions of the first metatarsal. This was to reduce soft tissue movement interference from the extensor digitorium longus, and extensor hallucis longus tendons. Second, a new rigid segment that represented the hallux as a three-dimensional segment was incorporated into this foot model. The reason for this was because of the functional importance of the movement of the first metatarsophalangeal joint during gait, and also due to the high prevalence of deformity of the first metatarsophalangeal joint.

With these modifications the Salford foot model used in this investigation represented six rigid segments: a. Hallux, b. Medial forefoot, c. Lateral forefoot, d. Midfoot, e. Calcaneus, f. Tibia

5.4.4 The manufacture of the Salford foot model plastic plates and placement of them on to the foot and leg

Individual plastic foot plates were manufactured for each rigid segment defined in the Salford foot model, with separate foot plates for right and left feet. To determine the size and shape of each plastic foot plate, plaster casts were taken of the different areas of the foot where the plates were to be positioned. This included the dorsal aspect of the foot which was from the metatarsal heads to the extensor retinaculum, and the medio-posterior-lateral aspect of the calcaneus from small and medium (size 4-5 and size 6) female feet and medium and large (size 9 and 12) male feet. The plaster casts were filled and allowed to dry. 2mm Suborothlene plastic was cut and shaped to form the dimensions of the different rigid segments of the foot. This was heat moulded onto the dried plaster casts. This aimed to provide the best possible contour with the different sections of the foot, and maximise the contact between the skin and the plastic. This would aim to create a secure base so to represent the different bony structure(s) of the foot underneath.

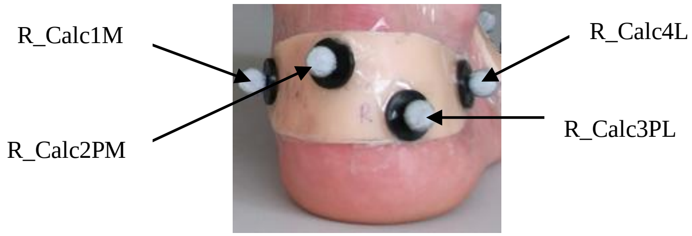
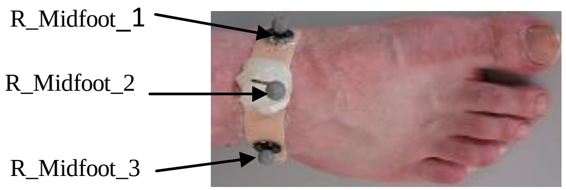
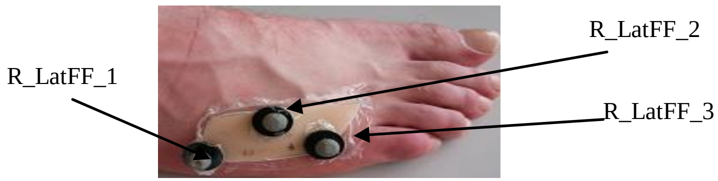
To ensure each foot plate was of an appropriate size, shape and provided a close contour with the foot they were fitted to ten (7 male) asymptomatic participants with no structural deformity so to represent the cohort of this investigation. All rigid plastic plates were initially secured to the foot with double sided sticky tape placed on the underside of each foot plate. Although, the foot plates fitted well and no participant reported any discomfort some participants reported that the calcaneus, midfoot and hallux plates began to move or loosen from the skin during walking. Gaffa tape (Onecall, Leeds) was used in conjunction with the double sided sticky tape to secure these foot plates to the skin of the foot. This aimed to ensure that the marker plates remained comfortable, and allowed normal movement of the foot during walking.

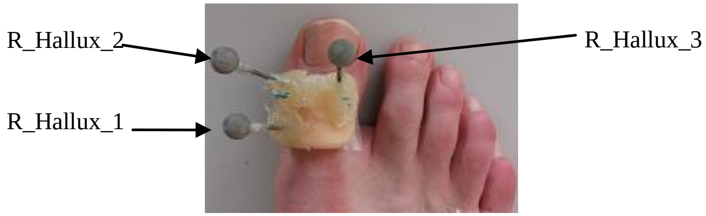
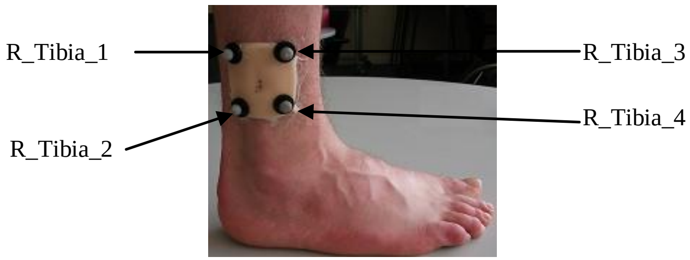
The placement of retro-reflective markers in this investigation was based upon the Calibrated Anatomical System Technique (CAST) (Cappozzo et al 1997). The CAST technique described in Cappozzo et al (1997) allows a local co-ordinate system that is defined by external markers to be given anatomical relevance. To do this requires two sets of markers. A technical marker set, which remain attached to the patient while the task to be recorded is performed. These are not related in any way to the anatomical point or plane of the structure(s) it is attached to but purely to define the position and orientation of it. Anatomical landmarks define anatomical features. These are placed overlaying anatomical landmarks in order to define the proximal and distal ends points of a segment. The placement of both sets of markers is specific to avoid skin marker artefact. Using these two marker sets the CAST technique will be able to reconstruct the global co-ordinate of each defined anatomical landmark during each frame of the task performed by using the co-ordinates obtained from the rotation and translation of the technical marker sets.

At least three technical markers were required to be attached to each rigid segment for its movement to be recorded during each walking trial. The size of all markers used was 7mm. This size was chosen because they were big enough to be captured by the infra-red cameras when placed on the foot, but small enough to allow the placement of other markers close to each other. This aimed to reduce to cross marker interference which would affect the quality of the data collected. The majority of rigid segments were defined with retro-reflective markers attached directly to the rigid plastic plate with double sided sticky tape. However, due to the small surface area of the foot and the number of rigid segments defined in the Salford foot model some retro-reflective markers were placed on short metal wire wands. These extended from some foot plates so to improve the capture of them and reduce inter-marker interference.

The placement of all rigid plastic plates onto the foot and the location of the markers attached to these are explained in Table 5.2.

Table 5.2 describes the placement of all foot plates and the location of the markers used to represent the six rigid segments of the Salford foot model

Name of rigid segment	**The bone(s) of the foot each rigid segment is designed to represent**	**The location of the foot plates on to the foot**	**The position of the technical markers attached to each foot plate**	**Photographic image of the placement of the foot plate onto the foot and the location of the retro-reflective technical markers attached to the dorsal aspect of each foot plate (*)**
Calcaneus	Calcaneus	The calcaneus plate extends from the midpoint of the medial aspect of the calcaneus around the posterior aspect of the calcaneus to the midpoint on the lateral aspect of the calcaneus	Four markers were attached directly onto the medial, lateral and posterior aspects of the calcaneus plate	
Midfoot	Navicular and Cuboid	The midfoot plate extends laterally from the tuberosity of the navicular across the midfoot to cover the cuboid	Two markers were attached directly onto the medial and lateral aspects of the midfoot and a wand marker extended centrally from the midfoot plate	
Lateral Forefoot	Fourth and Fifth metatarsals	The lateral forefoot plate extends proximally from the heads of the fourth and fifth metatarsals to the bases of both metatarsals	Three markers were attached directly onto the proximal, central and distal aspects of the lateral forefoot plate at logistically as possible distance from each other	

Medial Forefoot	First metatarsal	The medial forefoot plate extends distally from the head of the first metatarsal to the base of the first metatarsal. The section of the medial forefoot plate where R_MedFF_2 marker is placed is not in contact with the dorsal aspect of the foot so to reduce soft tissue movement interference from extensor hallucis longus.	Two markers were attached directly onto the medial forefoot plate overlaying the base of the first metatarsal and the central-lateral aspect of the first metatarsal. A wand marker extends from the medial forefoot plate at the central-medial aspect of the first metatarsal	
Hallux	Proximal phalanx of the hallux	The hallux plate partly wraps around the dorsal aspect of the proximal phalanx of the hallux	All markers were placed on wands that extended from the proximal and distal aspects of the hallux plate. Due to the small size of the plate positioning markers on the plate would not be feasible due to cross marker interference	
Tibia	Tibia (leg)	The tibial plate is a square plate which was situated on the lateral aspect of the leg approximately 5cm above the lateral mallelous. The lateral aspect of the leg was chosen to situate the tibial plate because of the least interference from the surrounding musculature.	Markers were attached at each corner of the tibial plate	

* Marker labels in all photographs represent the label name for the right foot only. For the left foot the "R" is replaced with "L" to represent for example "L_Calc_1M."

Figure 5.5 and 5.6 demonstrate an anterior, and posterior view of all Salford foot model foot plates attached to the foot and leg.

Anterior View

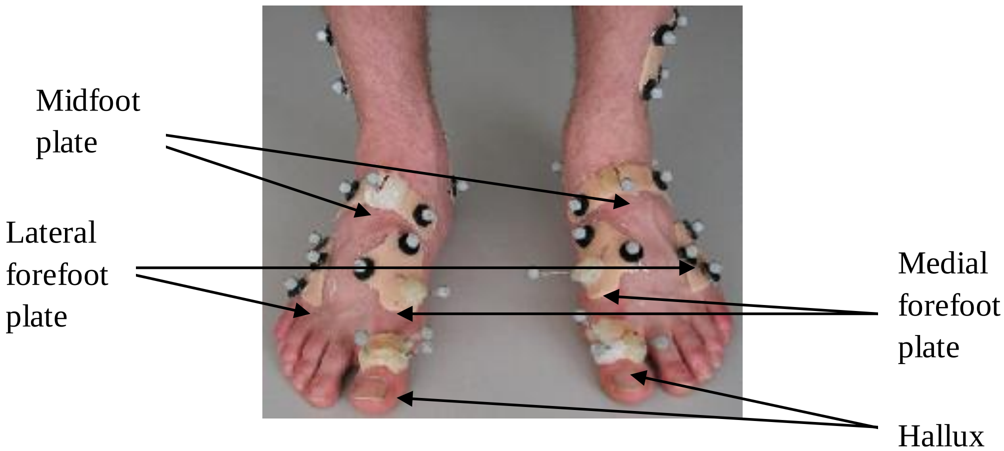


Figure 5.5 – Anterior view of all foot plates attached to a foot to represent the Salford foot model.

Posterior View

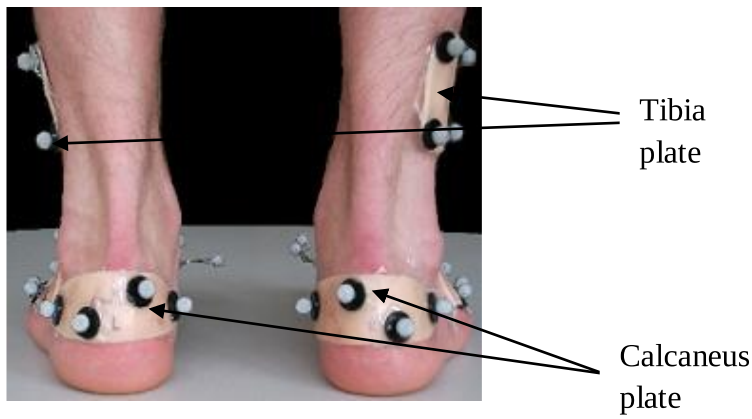


Figure 5.6 – Posterior view of all of the foot plates attached to a foot to represent the Salford Foot Model.

5.4.5 Placement of anatomical markers onto the foot and leg

Anatomical markers were attached to the leg following the basis to the CAST technique (Cappozzo et al 1997). These provide the necessary dimensions for the creation of the different rigid segments in the analysis software (Visual 3D analysis system (C-Motion, Rochelle, USA)) used for this investigation. Markers were placed on both limbs. They were positioned on the medial and lateral joint margins of the knee, and the medial and lateral malleoli as demonstrated by Figure 5.7 and 5.8.

Figure 5.7- Anterior view of the placement of the Salford foot model plates and all anatomical markers on the foot and leg

Figure 5.8 - Posterior view of the placement of the Salford foot model plates and all anatomical markers on the foot and leg

5.4.6 Analogue data capture

The primary use of the AMTI force plate (Type: BP400600, Dimensions: 600mm x 400mm) in this investigation was to determine the timing of initial heel contact, and toe off. Attached to the first infra-red camera was a 64 channel measurement computing analogue to digital board. This will receive the external digital devices (i.e the force plate data) which are captured with a measurement computing data translation card to capture simultaneous analogue and kinematic data.

5.4.7 Data Collection protocol

For both the static and dynamic trials the twelve infra-red cameras were started simultaneously using an external trigger which was activated for 10 seconds.

Data collection static trial

Anatomical and technical markers were attached to the participant. Two static standing trials were captured. First, with the participant standing in RCSP, this was used to define 0° of rotation. Second, with the participant standing in NCSP. The principal investigator followed the guidelines explained in Root et al (1971), and instructions from the podiatrist used to collect Data Set A to position both feet of the participant into NCSP.

All anatomical markers were subsequently removed for all walking trials.

Data collection walking trials

Each participant was instructed to walk in a straight line across the force plate. A successful trial was determined to be when only a single contact was made with the force plate. The start and end points of each walking trial allowed at least three gait cycles before, and after the contact of the foot with the force plate. Mueller and Strube (1996) stated that this distance should be allowed before the force plate so that when the participant makes contact with the force plate it is a good representation of their normal walking pattern and foot movement.

Each participant was instructed to do a series of “practice” walks before the start of the data collection. This allowed them to become accustomed to walking in the gait laboratory. Each subject completed 12 successful walking trials contacting the force plate with the right foot. Then, 12 successful walking trials contacting the force plate with the left foot. Kinematic data were collected at 100Hz and analogue data collected at 3000Hz. All data was collected was stored anonymously as each patient was given a patient number.

5.4.8 Data analysis

Digitisation of kinematic and kinetic data

Digitisation of all kinematic and kinetic data was performed in QTM program. The length of each walking trial collected by QTM program was reduced to a minimum of 10 frames before the first heel contact, and 10 frames after the second heel contact. This was because only one gait cycle was required per walking trial. From the 12 walking trials collected, 8 from each foot were digitised. If there were any erroneous problems, such as a marker missing or incorrect placement of the foot on the force plate, this walking trial was deleted and the next trial was selected.

The digitisation of all kinematic data in QTM program involved the identification of all static, and tracking markers from a pre-determined list of specifically named labels for each marker. To improve the efficiency of processing the large volume of kinematic data collected in this investigation an Automatic Identification of Markers model (AIM model) was used. An individual AIM model was saved for the right, and left of each participant. This was subsequently applied to each walking trial for that participant. Each walking trial was checked to ensure consistent marker labelling, and any errors were corrected. The position of each marker was checked throughout each trial. If there were any irregular movement of a marker, the trajectory of that marker was split at the time of the start of the irregular movement, and then split again when the marker regained its correct place. The maximum frame gap for which the QTM program would attempt to estimate the position of the marker within a deleted split frame was set to 10 frames. This is the recommended default value by the manufacturer's guidelines (QTM_Manual2.3). QTM program will gap fill (interpolate) within this frame gap by estimating the position of this marker. The estimated position of the marker was checked to ensure the movement seemed consistent with the movement of the marker before, and after the trajectory had been split, and the erroneous data had been removed.

All digitised static standing (RCSP and NCSP), and walking trials were exported as individual C3D signal files from QTM program.

5.5 Model building and data extraction from Visual 3D

The C3D signal files were imported into Visual 3D programme (C-Motion, Rochelle, USA) (Visual 3D). Visual 3D is a biomechanical software used to quantify three dimensional movement which has been captured using motion analysis software cameras, and will produce quantitative data for further analysis.

There are five stages to the processing of kinematic data in Visual 3D: a. Creation of model and segment definition, b. Signal processing, c. Definition of gait events, d.

Creation of inter-segmental angles, and calculation of inter-segmental angles, and e. Exportation of data from Visual 3D.

5.5.1 Creation of a model and segment definition

The creation of a rigid segment model in Visual 3D involves the definition of different rigid segments that are linked together by joints. This can then be measured relative to each other to create joint or inter-segmental angles. In Visual 3D each rigid segment is modelled as non-deformable, with six-degrees-of-freedom, and it is defined using the CAST technique. This assumes that each rigid segment can move in three translations (medio-lateral, anterior-posterior and vertically), and three rotations (sagittal, coronal and transverse) independently of all other rigid segments. This movement is not constrained by other rigid segments, or other structures.

For this investigation a seven segment six-degree-of-freedom model was created. This included the individual rigid segments of the foot and leg. Although the same model template was used for each participant, it was specific to the height and weight of each participant.

To measure the movement of all rigid segments defined in this investigation each segment was defined a local co-ordinate system. This was used to determine its position and orientation in three dimensional space. The method chosen to determine the position of a local co-ordinate system for each rigid segment is based on the CAST technique developed by Capozzzo et al (1997). This involves the definition of the proximal and distal end points of a rigid segment. These are typically anatomical landmarks at either end, and opposite ends of a rigid segment. This is where anatomical markers were placed during the collection of motion analysis data. The distance between the two markers placed at both the distal, and proximal end points of the rigid segment being defined is calculated. A line is then hypothetically drawn through the midpoint of both lines as displayed by Figure 5.9. This midpoint line is used to automatically represent the z axis (vertical), and at right angles to this is the x axis (medio-lateral). The position of the y axis (anterior-posterior) was computed by fitting a plane of least squares fit through the four locations, and it is the sum of squares distance between the locations and the frontal plane is minimised. It also represents the direction of walking movement by the participant. The location of the local co-ordinate system is at the proximal end point of the rigid segment.

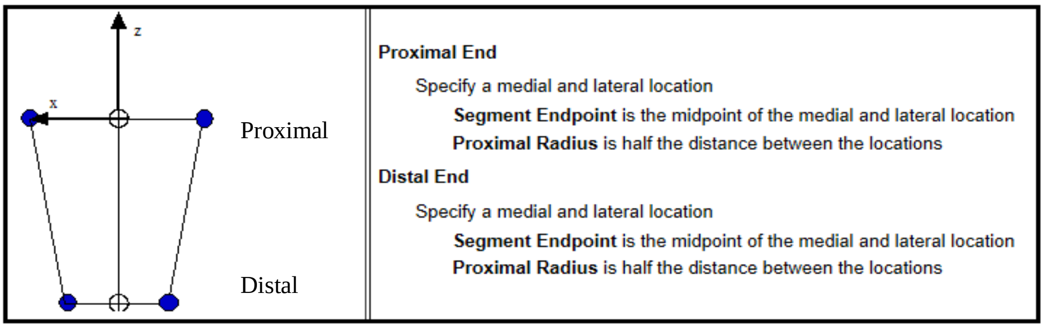


Figure 5.9 is adapted from C Motion (2012) and demonstrates the method chosen to determine the position of the local co-ordinate system used to define the position and orientation of a rigid segment

Using the method described previously is only possible when the segment is large enough, or can be easily defined by anatomical landmarks that can represent distal and proximal end points of this rigid segment. The individual rigid segments of the Salford foot model are small in size, and it was determined to not be possible without radiological confirmation to define specific anatomical landmarks. Other foot models discussed in Chapter 3, Section 3.5 have commonly used a single anatomical marker placed over a specific anatomical landmark to represent the origin of the local co-ordinate system for that rigid segment. However, Fuller (1997) and others (Chiari et al 2005, Karlsson and Tranburg 1999, Leardini et al 2005) have reported that correctly identifying a bony anatomical landmark is difficult, and erroneous. This is predominantly because of soft tissue structures and skin overlaying the bony landmark/tuberosity. As rigid plastic plates were used to overlay the rigid segments of the foot it was also determined to not be possible to correctly identify specific anatomical landmarks under these foot plates with markers. In consideration of these aforementioned difficulties the position and orientation of the local co-ordinate system assigned to the tibia, was used to define the position and orientation of the local co-ordinate system for all rigid segments of the Salford foot model. This allowed all rigid segments of the Salford foot model to be aligned, so that the computation of angles occurred around similar axes. The technical markers defined in Table 5.2 for each rigid segment of the Salford foot model where identified so that during each walking trial, Visual 3D could track the movement of each rigid segment.

5.5.2 Definition of the seven model of the foot and leg

The seven segment model comprised of a foot which was split into five rigid segments (hallux, medial forefoot, lateral forefoot, midfoot and calcaneus), tibia, and a virtual foot. The following is a description of the segment definitions, and co-ordinate systems for this model.

Definition of the position and orientation of the tibia segment

The position and orientation of the local co-ordinate system used to define the tibia segment was determined from a midpoint line. This was calculated from the midpoint between two distal end landmarks which are the medial and lateral malleoli, and two proximal end landmarks which are the medial and lateral margins of the knee. The technical markers of the tibia segment are placed on a cluster, and used for the motion of this segment.

Definition of the position and orientation of the individual rigid segments of the Salford foot model

Visual 3D currently provides only a one segment three-dimensional model of the whole foot, but it does allow the creation of an unrestricted number of individual rigid segments. Therefore, for this investigation it was possible to create a model of the foot, which included all five rigid segments of the Salford foot model. For the individual rigid segments of the Salford foot model, the technical markers that were placed directly onto the plastic foot plates that overlay each rigid segment were used for the motion of that segment. To define the position and orientation of the local co-ordinate system for each segment, the local co-ordinate system assigned for the tibia was used as per the description in Section 5.5.1.

Definition of the position and orientation of the virtual foot segment

A one segment virtual foot was also created for the measurement of ankle joint motion. The position and orientation of the local co-ordinate system used to define the foot segment was defined using proximal landmarks placed on the medial and lateral malleoli, and distal landmarks on the forefoot. The marker locations used were one of the medial forefoot segment markers (R(L)_MedFF3), and another from one of the lateral forefoot segment markers (R(L)_LatFF_3). However, when the participant is standing with a plantigrade foot, and a vertical shank the resulting angle of the local co-ordinate system of this foot segment is 70°. This is due to the alteration of the local co-ordinate system. Therefore, to ensure the data obtained from this segment was clinically meaningful, a virtual foot was created. To define the position and orientation of the virtual foot, the proximal and distal landmarks used to define the foot segment are transposed onto the laboratory floor. The local co-ordinate system created will be flat to the floor with a zero degree angle, and a 90° angle at the ankle joint.

5.5.3 Definition of zero (0°) reference position

A hybrid model was then created using the static standing RCSP trial to form the static calibration trial. The model template which contains all of the rigid segments was then applied to the static standing RCSP file to define each rigid segment. This determined the zero reference position of this model. Therefore, any movement of a segment during walking will be measured from this zero reference position. This model template was assigned to all walking trials, and the static standing trial of NCSP. The tracking markers were used to identify the movement of each rigid segment during walking, or the change in the position of each rigid segment when the subtalar joint was placed in a neutral position for NCSP.

5.5.4 Signal processing within Visual 3D

Although each imported C3D signal file had already undergone interpolation (gap-fill) within QTM program, there are still other factors that may affect the smoothness of the data. Robertson and Dowling (2003) described how Lowpass filtering with either a Butterworth or Critically dampened filter of a kinematic signal is an essential. They stated that this procedure will reduce noise, commonly caused by skin movement artefact and electrical interference. Robertson and Dowling (2003) stated that a Butterworth filter is often chosen to smooth kinematic data. This is because they are optimally flat in their pass band, have relatively high roll offs and rapid response in the time domain. In contrast, a critically dampened filter is more applicable for signals with rapid transitions such as accelerometer data. Therefore, for this investigation a Bi-directional Butterworth Lowpass filter was selected, with a cut off frequency of 6Hz.

5.5.5 Definition of gait events in Visual 3D

To define the stance and swing phase of the gait cycle within each file, the force plate was used to identify the timing of initial heel contact and toe off. When the force recorded was greater than 10N, it was determined that this was initial heel contact and the beginning of the stance phase. When the force was less than 10N it signified toe off, and the end of the stance phase. Each walking trial was checked to ensure Visual 3D had correctly assigned the timing of initial heel contact and toe off. However, because only one force plate was used in this investigation the timing of the second heel contact (initial heel contact (2)) at the end of the swing phase had to be defined using automatic gait events. This uses a target pattern recognition theory implementation developed by Stanhope et al (1990). This involves calculating the angle of the foot at initial heel contact by using the trajectory of the proximal end point of the foot segment. Then when the foot reaches this angle again after the swing phase, it is defined as the second heel contact.

5.5.6 Calculation of inter-segmental angles

Seven inter-segmental angles were calculated in Visual 3D for this investigation, and what they represent is presented in Table 5.5.3. To calculate the angle, or the movement of an inter-segmental angle, one segment was defined as the reference segment. Therefore it is the local co-ordinate system of this segment used as the frame of reference. The movement of the other segment is compared relative to this segment through a series of rotational transformations around the different axes of the defined local co-ordinate system. For this investigation, an X-Y-Z Cardan sequence was applied. This describes sagittal plane motion around an x axis, frontal plane motion around a y axis, and transverse plane motion around a z axis. This is similar to that described by Grood and Suntay (1983).

For all inter-segmental angles calculated it was essential that the segmental angles calculated, displayed graphically and exported represented the same movement. Therefore, for all individual inter-segmental angles of the foot and for the whole foot positive angles donate dorsiflexion, inversion and abduction, and negative angles donate plantarflexion, eversion and adduction. The angle of all inter-segmental angles in the relaxed static standing was minused from the angle of each inter-segmental angle for each of the 0-100% individual points of the time series data.

	Name of inter-segmental angle					
	Calcaneus-Tibia	**Midfoot-Calcaneus**	**Lateral FF-Midfoot**	**Medial FF-Midfoot**	**Hallux-Medial FF**	**Foot-Tibia**
Reference segment	Tibia	Calcaneus	Midfoot	Midfoot	Medial forefoot	Tibia
Segment	Calcaneus	Midfoot	Lateral forefoot	Medial forefoot	Hallux	Foot
What each inter-segmental angle aims to represent anatomically	Ankle and subtalar joint	Midtarsal joint	Fourth and fifth metatarsals relative to midfoot	First metatarsal relative to midfoot	First MTPJ	Ankle joint

Table 5.3 presents the seven inter-segmental angles calculated in this investigation and what each inter-segmental angle aims to represent anatomically. MTPJ: Metatarsophalangeal joint

5.6 Data analysis and extraction of key parameters in Matlab

A custom built Matlab R2009b (Mathworks) (Matlab) script was instructed to import an individual Matfile either for the right or left foot of each participant. It was then stored within the Matlab workspace as a matrix. Key parameters were then extracted from each inter-segmental angles within this Matfile, and exported to a specifically designed Microsoft Excel spreadsheet.

The parameters to be extracted were determined from the Root et al hypotheses and hypotheses that form Research Question One and Two as stated in Chapter 3 of this investigation. They also include what is consistently reported by other investigations (Cornwall and McPoil 1999a, Leardini et al 2007 and DeMits et al 2012, Hunt et al 2001a, Rattanaprasert et al 1999, Simon et al 2006, Carson et al 2001, Jenkyn and Nicol 2007) when describing the kinematics of the foot and leg. Before this could be achieved specific gait events had to be determined which were then used to extract these parameters.

5.6.1 Identification of the timing of specific gait events

The gait events to be determined included the different stages of the gait cycle (initial heel contact, forefoot loading, heel lift, toe off and initial heel contact (2), and the different phases of the gait cycle (contact, midstance, propulsion and swing phase). The calculation of the timing of the stages of the gait cycle automatically calculated the timing, and length of the different phases of the gait cycle.

The timing of initial contact and toe off were previously identified from Visual 3D, and initial heel contact (2) represented the last point of the signal. To identify the timing of forefoot loading, and heel lift the movement of the ankle joint in the sagittal plane was used.

Richards (2008) and Perry (1992) described how at the end of the contact phase when the forefoot makes flat plantigrade contact with the supporting surface to represent forefoot loading the ankle joint is simultaneously plantarflexed to an initial peak angle for early stance. At heel lift, Nester et al (2006), Lundgren et al (2007) and Arndt et al (2004) reported that the ankle joint reached a peak angle of dorsiflexion for the whole stance phase. When the heel begins to lift from the supporting surface it represents the end of midstance and beginning of propulsion.

. A custom built Matlab script was instructed to identify these gait parameters using this ankle joint matrice for each walking trial. It was first instructed to identify the peak angle of plantarflexion between 0-50% of the stance phase as identified by the green circle on Figure 5.10. Then instructed to identify the peak angle of dorsiflexion during the stance phase, as identified by the red circle on Figure 5.10.

This graph (Figure 5.10) was produced for each individual walking trial. Each graph was visually checked to ensure Matlab had identified the correct peak angles. The timing of these gait events were individual percent values on the gait cycle time frame from 0-100% for each individual walking trial. These were then stored as individual cells within a row vector within the Matlab workspace.

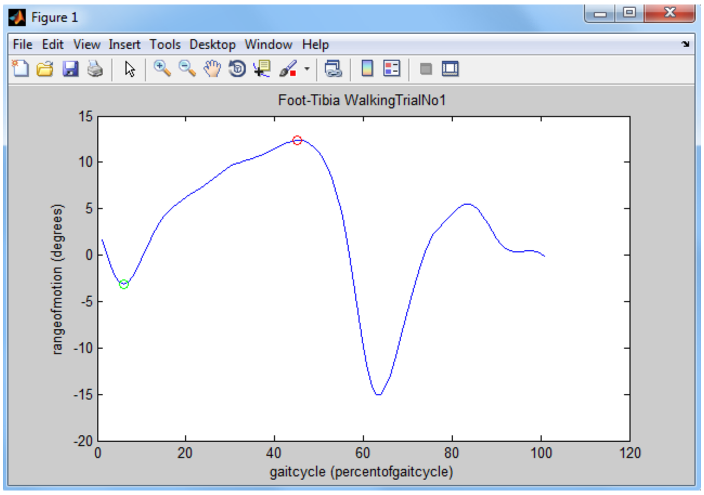


Figure 5.10 – An example graph from Matlab demonstrating the movement of the ankle joint in the sagittal plane during the gait cycle with the peak angle of initial plantarflexion (green circle) and peak angle of dorsiflexion (red circle) identified.

With the timing of forefoot loading, and heel lift specified it was possible to identify four distinct phases of the gait cycle. The contact phase was defined from initial heel contact to forefoot loading. Midstance was defined as from forefoot loading to heel lift. Propulsion was defined from heel lift to toe off. The swing phase was defined from toe off to initial heel contact (2).

5.6.2 Extraction of key parameters from each inter-segmental angles using the specific gait events

Using the gait events previously defined the sagittal, frontal and transverse plane angle of each inter-segmental angle was extracted using a custom built Matlab code.

Gait parameters were extracted from these at each stage of the gait cycle, the peak positive and peak negative angle, and timing of these peak angles during each phase of the gait cycle.

These extracted parameters from each inter-segmental angle were exported to a specifically designed Microsoft Excel spreadsheet. Individual Microsoft Excel spreadsheets were constructed for the right, and left feet of each participant. Each Microsoft Excel spreadsheet was checked to ensure that the correct data had been exported to the correct cells within that Microsoft Excel spreadsheet.

Within this Microsoft Excel spreadsheet the range of motion was calculated using the peak positive, and peak negative angles from each phase of the gait cycle with the equation:

Total range of motion within a phase of the gait cycle = second peak angle – first peak angle

5.6.3 Calculation of mean values

A custom built Matlab script was instructed to calculate the mean of each exported parameter for the eight walking trials processed for each participant. This was then exported to a series of Microsoft Excel spreadsheets which contained the mean values for each participant for a specific inter-segmental angle.

The position of each inter-segmental angle when the individual was standing in RCSP was exported as an ASCII file from Visual 3D. The mean value for each inter-segmental angle was then calculated and then was minused from the mean joint angle of each inter-segmental angle manually within Microsoft Excel. This ensures that the joint angle of an inter-segmental angle during walking is measured from 0° and does not account for the position of that inter-segmental angle in RCSP.

5.7 Statistical analysis

All data required for each individual hypothesis was collated into separate Microsoft Excel spreadsheets, and then processed through Statistical Package Social Science Software (Version 17.0) (SPSS, Chicago, Illinois, USA).

For each hypothesis the required data from Data set A and/or Data set B were checked for normal distribution using the Kolmogorov-Smirnov test. A significant p value of less than 0.05 was determined to indicate that the sample is not normally distributed. However, Field (2009) reported that a weakness of the Kolmogorov-Smirnov test is that when sample sizes are quite large, it is possible to get small deviations from the proposed normality. This can cause a significant result but it does not necessarily indicate as to whether it is enough to incur bias on any statistical procedures that will be conducted on the data tested. Therefore, in addition all data was checked for Skewness and Kurtosis. Both scores were converted into z scores and the resultant value had to be less than 1.96 for the data to be classified as normally distributed as suggested by Field (2009).

All data classified as normally distributed was suitable for parametric statistical analysis. For all data classified as not normally distributed the non-parametric equivalent of the required parametric test was used. All hypotheses from Research Question 2 were classified as directional, and therefore the statistical model applied is one tailed and this was applied to all statistical tests conducted. The significance value was set at 0.05, unless otherwise stated.

5.7.1 Statistical analysis for the presentation of inter-segmental angle data

The mean, standard deviation and 95% confidence interval of all right, and then all left feet for all of the gait parameters defined in Data set B which are described in Chapter 5, Section 5.4 were calculated in SPSS. For a comparison between the results from two different gait parameters, the data was firstly checked for normality. If the data to be used was determined to be normally distributed an independent t-test was used, and if the data was determined to not be normally distributed the Mann-Whitney test was selected.

5.7.2 Statistical analysis for Research Question 1

The mean, standard deviation and 95% confidence interval of all right, and then all left feet for each gait parameter used in each hypothesis were calculated in SPSS. The maximum and minimum values, the number, and percentage of feet demonstrating either direction of an angle, or plane of motion for each gait parameter were calculated in Microsoft Excel.

For a comparison between the results from two different gait parameters, the data was firstly checked for normality. If the data to be used was determined to be normally distributed an independent t-test was used and if the data was determined to not be normally distributed the Mann-Whitney test was selected.

5.7.3 Statistical analysis for Research Question 2

The mean, standard deviation and 95% confidence interval of all right and then all left feet for each measurement from Data Set A, and each gait parameter from Data Set B used in each hypothesis were calculated in SPSS. The maximum and minimum values, the number and percentage of feet demonstrating either direction of an angle or plane of motion for each gait parameter used in each hypothesis were calculated in Microsoft Excel.

To determine the strength of the relationship between a gait parameter (Data Set B), and a measurement from the static based biomechanical examination of the foot (Data Set A), a Pearson's correlation coefficient (r) was selected for normally distributed data. A Spearman's correlation coefficient (s) was selected for non-normally distributed data.

To determine the difference between a measurement obtained from the static based biomechanical assessment of the foot (Data Set A), and the relevant gait parameter (Data Set B) the data was firstly checked for normality. If the data to be used was determined to be normally distributed an independent t-test was selected. If the data was determined to not be normally distributed, the Mann-Whitney test was selected. In conjunction with this, Levene's test for equality of variances was used to determine if there are equal variances between the data tested. If Levene's test for equality of variances was significant, the result for the significance value for the equal variances are not assumed statistical test was used.

To compare the measurements from Data Set A or gait parameters from Data Set B in feet classified with or without a structural deformity the data to be used was firstly checked for normality. If there are only two classifications of feet (for example forefoot varus or no forefoot deformity), and the data to be used was determined to be normally distributed an independent t-test was selected. If the data was determined to not be normally distributed the Mann-Whitney test was selected. In conjunction with this Levene's test for equality of variances was used to determine if there are equal variances between the groups. If Levene's test for equality of variances was significant, the result for the significance value for the equal variances are not assumed statistical test was used. This was deemed particularly useful, as in some instances there were large differences in the sample size of the classifications of feet.

For a comparison between three classifications of feet (for example plantarflexed first ray flexible, plantarflexed first ray rigid, or no forefoot deformity), and if the data to be used was determined to be normally distributed, a One Way ANOVA was used. Levene's test for equality of variances was also used for each comparison and followed the guidelines described previously. If Levene's test for equality of variances was non-significant, the post hoc test selected was the Least Significant difference test. If Levene's test for equality of variances was significant, Tamahanes T2 test was selected for post hoc analysis. If the data was not normally distributed, and there were three classifications of feet, the Kruskal-Wallis test was used. For post hoc analysis, individual Mann-Whitney tests were conducted between two classifications of feet. This was until all classifications of feet had been compared against each other. To determine the significance level of these post hoc tests a similar method to the Bonferroni correction was applied. This is where the significance value which is 0.05 is divided by the number of tests for that comparison. This will determine what difference between individual groups can be determined to be significant. Field (2009) suggested that this will help to avoid Type

1 errors which are often incurred when a large number of individual comparisons are made. Although, this can result in very low p values depending on the number of tests to completed. However, for this investigation there were no more than three different classifications of feet per comparison.

CHAPTER SIX – RESULTS AND DISCUSSION

6.1 Overview

Chapter 6 presents the results from this investigation, and a discussion of these with the relevant literature. This chapter is divided into five main sections. The first section presents the demographics of the participants included in this investigation. The second section presents all inter-segmental angles calculated within the foot. There is no reference to Root et al (1971, 1977) within this section. The third section presents the results from this investigation, and a discussion of these from other literature resources for each Root et al hypothesis in Research Question 1. The fourth section presents the results from this investigation, and a discussion of these from other literature resources for each hypothesis in Research Question 2. This aims to determine the strength of the relationship between the measurements, or classification of the foot from the static based biomechanical assessment of the foot (Data Set A), and the kinematic motion of the foot and leg from Data Set B. The fifth section presents the overall conclusions of this investigation and with this a description of the clinical implications of it and suggested future work.

6.1.1 Introduction to terminology used to present results in Chapter 6

For the presentation of the results in each section of Chapter 6 there is specific terminology used, and this is an explanation of these.

For each plane of motion within each hypothesis a positive direction of a range of motion is described as dorsiflexion, inversion or abduction. A negative direction of a range of motion is described as plantarflexion, eversion or adduction. A positive direction of an angle is described as dorsiflexed, inverted or abducted. A negative direction of an angle is described as plantarflexed, everted or adducted.

To represent pronation, or supination at the subtalar joint the range of frontal plane motion of the calcaneus relative to the tibia was used. To represent a pronated or supinated angle at the subtalar joint the frontal plane angle of the calcaneus relative to the tibia was used.

To represent pronation or supination at the midtarsal joint in Research Question 2 the range of frontal plane motion of the midfoot relative to the calcaneus was used. To represent a pronated or supinated angle at the midtarsal joint in Research Question 2 the frontal plane angle of the midfoot relative to the calcaneus was used.

The additional descriptive analysis included within most tables, and table legends presented for each hypothesis in Research Question 1 and 2 are the number of, and percentage of feet demonstrating a direction of motion or angle for each plane of motion for that parameter.

These are presented within a table as:

No. of feet DF/PF, INV/EVER, ABD/ADD (n,%)

Within the legend of the table:

The number of feet displaying range or angle of DF/PF, INV/EVER, ABD/ADD (n,%).

For data describing the results in the sagittal plane from Data Set A, this represents the number of feet and percentage of feet that were measured in a dorsiflexed or plantarflexed angle. For data from Data Set B, this represents the overall number of feet and percentage of feet that were in a dorsiflexed, or plantarflexed angle at a specific stage of the gait cycle, or were dorsiflexing or plantarflexing during a phase of the gait cycle for each gait parameter from Data Set B.

For data describing the results in the frontal plane from Data Set A, this represents the number of feet and percentage of feet that were measured in a inverted or everted angle. For data from Data Set B, this represents the overall number of feet and percentage of feet that were in an inverted or everted angle at a specific stage of the gait cycle or those that were inverting or everting during a phase of the gait cycle for each gait parameter from Data Set B.

For data describing the results in the transverse plane from Data Set B, this represents the overall number of feet and percentage of feet that were in a abducted or adducted angle at a specific stage of the gait cycle or those that were abducting or adducting during a phase of the gait cycle for each gait parameter from Data Set B.

The additional descriptive analysis included within most tables and table legends presented for each hypothesis in Research Question 1 and 2 are the maximum and minimum angle, or range of motion for each plane of motion for that parameter.

These are presented within a table as:

Max/Min DF/PF, INV/EVER, ABD/ADD (°).

Within the legend of the table:

The Max/Min range or angle of DF/PF, INV/EVER, ABD/ADD (°).

For data describing the results in the sagittal plane from Data Set A, this represents the maximum (or minimum) dorsiflexed or plantarflexed angle demonstrated by any foot from the cohort, or the maximum (or minimum) range of dorsiflexion or plantarflexion demonstrated by any foot from the cohort. For data from Data Set B, this represents the maximum (or minimum) dorsiflexed or plantarflexed angle demonstrated by any foot from the cohort at a specific stage of the gait cycle, or the maximum (or minimum) range of dorsiflexion or plantarflexion demonstrated by any foot from the cohort during a phase of the gait cycle for each gait parameter from Data Set B.

For data describing the results in the frontal plane from Data Set A, this represents the maximum (or minimum) inverted or everted angle demonstrated by any foot from the cohort or the maximum (or minimum) range of inversion or eversion demonstrated by any foot from the cohort. For data from Data Set B, this represents the maximum (or minimum) inverted or everted angle demonstrated by any foot from the cohort at a specific stage of the gait cycle, or the maximum (or minimum) range of inversion or eversion demonstrated by any foot from the cohort during a phase of the gait cycle for each gait parameter from Data Set B.

For data describing the results in the transverse plane from Data Set B this represents the maximum (or minimum) abducted or adducted angle demonstrated by any foot from the cohort at a specific stage of the gait cycle, or the maximum (or minimum) range of abduction or adduction demonstrated by any foot from the cohort during a phase of the gait cycle for each gait parameter from Data Set B.

6.2 Participant demographics from this investigation

All participants included in this investigation were classified as asymptomatic from the screening assessment explained in Chapter 5, Section 5.2.

In total 100 participants were included in this investigation with a mean age of 31.7 years (SD = 15.4 years), a mean height of 168.3cm (SD = 8.1cm) and a mean weight of 71.8kg (14.0kg). The mean Body Mass Index for all participants included in this cohort was 25.3.

		All Participants (Male and Female)	**Female Participants**	**Male Participants**
	Number of participants(n)	n=100	n=71	n=29
Age (years)	Mean	31.7	31.5	32.3
	SD	*15.4*	*14.7*	*17.1*
	95% CI	*28.5- 35.1*	*27.7- 35.3*	*25.7- 38.9*
Height (cm)	Mean	168.3	164.8	176.9
	SD	*8.1*	*5.4*	*6.9*
	95% CI	*166.7- 169.9*	*163.5- 166.1*	*174.2- 179.5*
Weight (kg)	Mean	71.8	68.0	81.0
	SD	*14.0*	*13.1*	*12.0*
	95% CI	*69.0- 74.6*	*64.9- 71.2*	*76.5- 85.6*
Activity Level	Mean	*3.2*	*3.1*	*3.4*
	SD	*0.9*	*0.9*	*1.2*
	95% CI	*2.9- 3.4*	*2.9- 3.3*	*2.9- 3.8*

Table 6.1 presents the participant demographics for all participants included in this investigation

6.3 Results and Discussion - Inter-segmental angle data

The inter-segmental angles presented in Tables 6.2, 6.3, 6.4, 6.5 and 6.6 describe the movement of the calcaneus relative to the tibia, midfoot relative to calcaneus, lateral forefoot relative to midfoot, medial forefoot relative to midfoot, and hallux relative to medial forefoot. This data is provided for the different stages of the gait cycle (initial heel contact, forefoot loading, heel lift, propulsion, initial heel contact (2)) and phases of the gait cycle (contact, midstance, propulsion, swing phase), and the peak positive (peak +ve) angle of dorsiflexion, inversion, abduction and peak negative (peak –ve) angle of plantarflexion, eversion and adduction, and timing of this angle within each phase of the gait cycle. Following this there is a discussion with comparison of the data with existing literature. As this data is the source kinematic data that was used to test each individual Root et al hypothesis from Research Question 1, and hypotheses in Research Question 2 it was deemed important to present the results for each inter-segmental angle calculated within the foot. This allows them to be compared to the existing literature, and demonstrate their suitability for providing conclusions to Research Question 1 and 2 in the following sections.

6.3.1 Calcaneus relative to the tibia

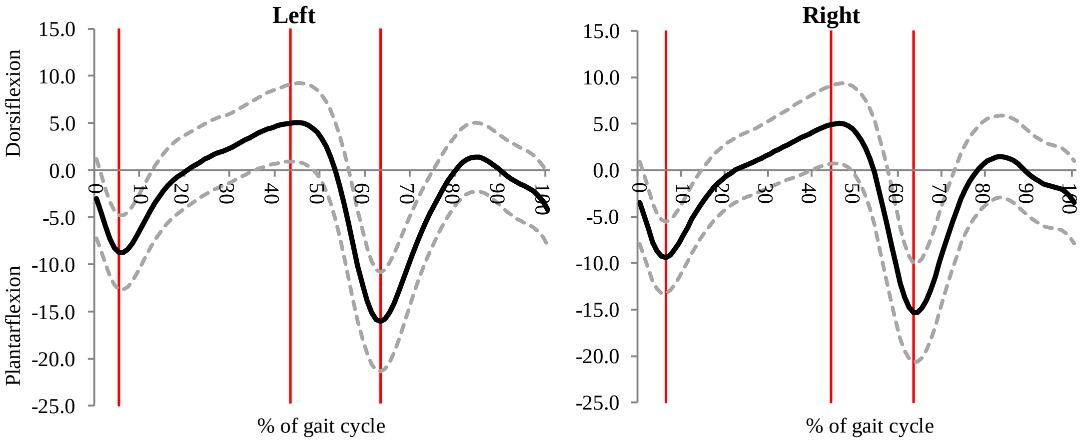


Figure 6.1a (left) and 6.1b (right): Sagittal plane movement of the calcaneus relative to the tibia during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

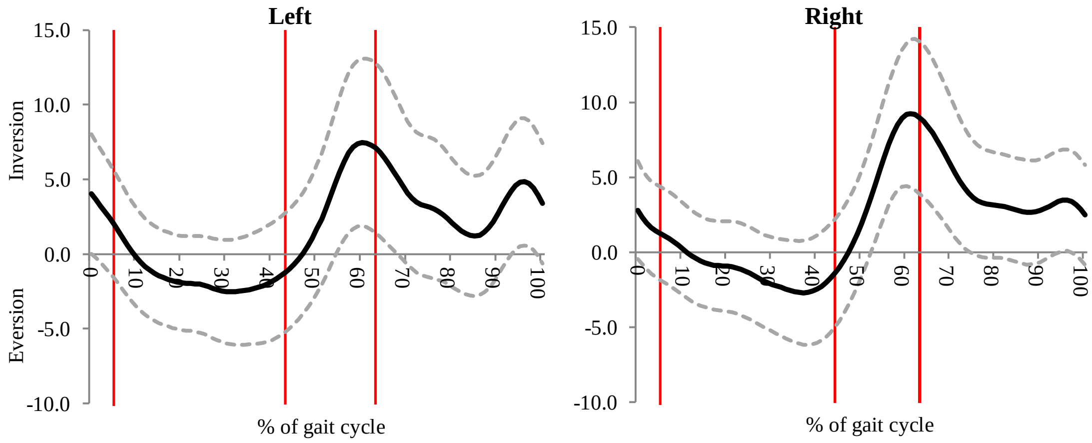


Figure 6.1c (left) and 6.1d (right): Frontal plane movement of the calcaneus relative to the tibia during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

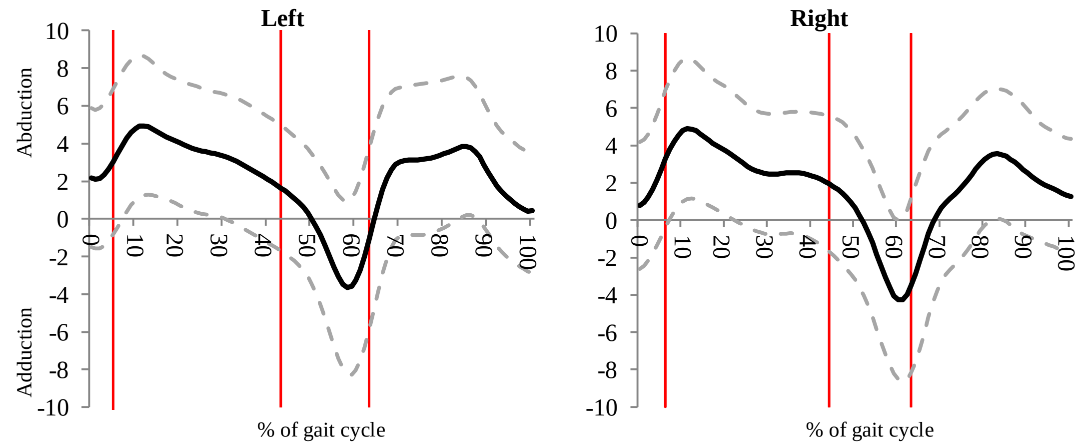


Figure 6.1e (left) and 6.1f (right): Transverse plane movement of the calcaneus relative to the tibia during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

Contact phase

The calcaneus was plantarflexed, inverted and adducted relative to the tibia at initial heel contact (left: sagittal = -3.1° (SD = 4.2°), frontal = 4.0° (SD = 4.0°), transverse = 2.2° (SD = 3.7°)), and forefoot loading (left: sagittal = -8.9° (SD = 3.9°), frontal = 1.9° (SD= 3.6°), transverse = 3.1° (SD= 3.9°)) (Figures 6.1-6.6). During the contact phase Figures 6.1a-6.1f demonstrate that it plantarflexed (left: -5.9° (SD = 2.4°)), everted (left: -2.2° (SD = 1.7°)) and abducted (left: 1.1° (SD= 2.2°)).

Midstance

The calcaneus dorsiflexed (left: 14.8° (SD = 3.2°)), everted (left: -4.5° (SD = 5.3°)) and adducted (left: -1.9° (SD = 6.1°)) relative to the tibia during midstance as demonstrated by Figures 6.1a-6.1f. At heel lift it was in a dorsiflexed (left: 5.6° (SD = 4.0°)), everted (left: -0.9° (SD = 4.0°)) and abducted (left: 1.9° (SD = 3.5°)) (Figures 6.1-6.6). Compared to the angle at heel lift, the calcaneus was -3.1° (SEM=0.5), ($p = <0.0001$) on the left, and -2.9° (SEM = 0.5), ($p = <0.0001$) on the right more everted relative to the tibia at the peak angle of eversion during midstance. As demonstrated by Figure 6.1a-6.1f, this indicates, that from this reaching a peak angle of eversion, most feet have then inverted during the latter stages of midstance. Inter-participant variation in the angle and range of frontal and transverse plane motion during this phase is demonstrated by the large standard deviation values. The range of sagittal plane motion during this phase is considerably greater and demonstrates far less inter-participant variation.

Propulsion

During propulsion the calcaneus plantarflexed (left: -22.9° (SD = 4.8°)), inverted (left: 9.6° (SD = 5.4°)) and adducted (left: -6.6° (SD = 4.9°)) relative to the tibia. At toe off it was plantarflexed (left: -17.2° (SD = 5.3°)), inverted (left: 6.8° (SD= 6.4°)) and adducted (left: -1.8° (SD = 5.1°)) (Figures 6.1a-6.1f). The peak angle of inversion is 2.2° (SEM = 0.4), ($p = 0.001$) on the left, and 1.0° (SEM = 0.9), ($p = 0.07$) on the right greater than the angle at toe off. This indicates that the calcaneus has everted relative to the tibia towards the end of propulsion, which is demonstrated by Figure 6.1a-6.1f. As in midstance, the range of sagittal plane motion was much greater than the range of frontal and transverse plane motion.

Swing phase

The calcaneus dorsiflexed (left: 19.5° (SD = 5.2°)), everted (left: -5.1° (SD= 7.8°)) and abducted (left: 3.6° (SD = 8.4°)) relative to the tibia during the swing phase.

Gait Parameter	Descriptive Analysis (+ve angle/ ROM DF, INV, ABD)	(+ve DF, -ve PF) Sagittal (x)		(+ve INV, -ve EVER) Frontal (y)		(+ve ABD, -ve ADD) Transverse (z)	
		Left	**Right**	**Left**	**Right**	**Left**	**Right**
Angle at initial heel contact	Mean (SD) (°)	-3.1 (4.2)	-3.5 (4.4)	4.0 (4.0)	2.8 (3.2)	2.2 (3.7)	0.8 (3.4)
	95% CI (°)	*-3.9 - -2.2*	-4.6 - -2.6	*3.2 - 4.8*	2.2 - 3.5	*1.5 - 2.9*	0.1- 1.5
ROM during contact phase	Mean (SD) (°)	-5.9 (2.4)	-6.2 (2.4)	-2.2 (1.7)	-1.7 (2.1)	1.1 (2.2)	*2.4 (2.5)*
	95% CI (°)	*-6.4- -5.5*	*-6.7- -5.7*	*-2.5- -1.8*	*-2.1- -1.3*	*0.7- 1.6*	*1.9- 2.9*
Peak +VE contact phase	*Mean (SD) (°)*	*-3.0 (4.2)*	*-3.5 (4.5)*	*4.2 (3.8)*	*3.2 (3.2)*	*3.7 (3.8)*	*3.4 (3.8)*
	95% CI (°)	*-3.9 - -2.2*	*-4.4 - -2.6*	*3.5 - 5.0*	*2.6 - 3.8*	*2.9 - 4.4*	*2.0 - 4.1*
Peak +VE time of contact phase	*Mean (SD) (°)*	*1.0 (0.1)*	*1.1 (0.2)*	*1.9 (1.4)*	*2.3 (1.9)*	*4.6 (2.1)*	*5.6 (2.0)*
	95% CI (°)	*1.0 - 1.1*	*1.0 - 1.1*	*1.6 - 2.2*	*1.9 - 2.7*	*4.1 - 4.9*	*5.2 - 6.0*
Peak -VE contact phase	*Mean (SD) (°)*	*-9.1 (3.9)*	*-9.7 (4.0)*	*1.8 (3.7)*	*0.8 (3.1)*	*1.5 (2.1)*	*0.4 (3.3)*
	95% CI (°)	*-9.8 - -8.2*	*-10.4 - -8.9*	*1.0 - 2.5*	*0.2 - 1.5*	*0.7 - 2.2*	*-0.3 - 1.0*
Peak +VE time of contact phase	*Mean (SD) (°)*	*6.2 (1.1)*	*6.5 (1.3)*	*5.5 (1.5)*	*5.1 (1.7)*	*2.9 (1.7)*	*2.2 (1.4)*
	95% CI (°)	*6.0 - 6.5*	*6.2 - 6.7*	*5.2 - 5.8*	*4.7 - 5.4*	*2.5 - 3.2*	*1.9 - 2.4*
Angle at forefoot loading	Mean (SD) (°)	-8.9 (3.9)	-9.6 (3.8)	1.9 (3.6)	1.3 (3.2)	3.1 (3.9)	3.1 (3.9)
	95% CI (°)	*-9.8 - -8.2*	*-10.4 - -8.9*	*1.3 - 2.7*	*0.7 - 1.9*	*2.3 - 3.9*	*2.3 - 3.9*
ROM during midstance	Mean (SD) (°)	14.8 (3.2)	15.4 (3.5)	-4.5 (5.3)	-4.3 (4.4)	-1.9 (6.1)	-2.7 (5.5)
	95% CI (°)	*14.2 - 15.5*	*14.7 - 16.1*	*-5.5 - -3.4*	*-5.2 - -3.4*	*-3.2 - -0.77*	*-3.8 - -1.6*
Peak +VE midstance	*Mean (SD) (°)*	*5.8 (3.9)*	*5.7 (4.2)*	*2.6 (3.6)*	*2.0 (2.9)*	*6.4 (3.3)*	*6.1 (3.5)*
	95% CI (°)	*4.9 - 6.6*	*4.8 - 6.5*	*1.8 - 3.3*	*1.4 - 2.6*	*5.7 - 7.0*	*5.4 - 6.8*
Peak +VE time of midstance	*Mean (SD) (°)*	*41.8 (5.7)*	*44.4 (4.6)*	*14.1 (11.4)*	*18.4 (10.7)*	*20.0 (9.8)*	*19.9 (10.6)*
	95% CI (°)	*40.7 - 42.9*	*47.5 - 45.4*	*11.8 - 16.4*	*16.3 - 20.5*	*18.5 - 22.4*	*17.8 - 22.0*
Peak -VE midstance	*Mean (SD) (°)*	*-9.0 (3.9)*	*-9.7 (3.8)*	*-3.9 (3.3)*	*-3.7 (3.3)*	*0.4 (3.3)*	*0.3 (3.0)*
	95% CI (°)	*-9.8 - -6.3*	*-10.5- -8.9*	*-4.7- -3.3*	*-4.4 - -3.1*	*-0.3 - 1.1*	*-0.3 - 0.9*
Peak -VE time of midstance	*Mean (SD) (°)*	*6.8 (1.1)*	*7.1 (1.3)*	*28.8 (7.7)*	*32.4 (7.4)*	*28.0 (14.1)*	*29.4 (13.3)*
	95% CI (°)	*6.5 - 7.0*	*6.8 - 7.3*	*27.2 - 30.4*	*30.9 - 33.8*	*25.2 - 30.8*	*26.8 - 32.0*
Angle at heel lift	Mean (SD) (°)	5.6 (4.0)	5.5 (4.2)	-0.9 (4.0)	-0.8 (3.7)	1.9 (3.5)	2.0 (3.6)
	95% CI (°)	*4.8 - 6.4*	*4.7 - 6.4*	*-1.6 - -0.6*	*-1.5 - -0.1*	*1.3 - 2.6*	*1.3 - 2.7*
ROM during propulsion	Mean (SD) (°)	-22.9 (4.8)	-21.9 (4.4)	9.6 (5.4)	11.1 (3.8)	-6.6 (4.9)	-7.9 (3.4)
	95% CI (°)	*-23.9 - -21.9*	*-22.8 - -21.1*	*8.5 - 10.7*	*10.3 - 11.8*	*-7.6 - -5.6*	*-8.6- -7.3*
Peak +VE propulsion	*Mean (SD) (°)*	*5.7 (4.0)*	*5.6 (4.2)*	*8.9 (5.2)*	*10.2 (4.6)*	*2.6 (3.4)*	*2.5 (3.8)*
	95% CI (°)	*4.9 - 6.5*	*4.8- 6.5*	*7.9 - 9.9*	*9.2 - 11.1*	*1.88 - 3.2*	*1.8 - 3.3*
Peak +VE time of propulsion	*Mean (SD) (°)*	*44.5 (4.8)*	*46.4 (4.0)*	*59.9 (3.7)*	*61.0 (2.9)*	*48.1 (6.9)*	*48.3 (5.6)*
	95% CI (°)	*45.5 - 45.4*	*45.6 - 47.2*	*59.2 - 60.6*	*60.4 - 61.6*	*46.8 - 49.5*	*47.2 - 49.4*
Peak -VE propulsion	*Mean (SD) (°)*	*-17.1 (5.2)*	*-16.3 (5.2)*	*-1.4 (4.1)*	*-0.9 (3.6)*	*-5.0 (4.3)*	*-5.5 (3.9)*
	95% CI (°)	*-18.2 - -16.1*	*-17.4 - -15.3*	*-2.2 - -0.5*	*-1.7- -0.3*	*-5.9 - -4.2*	*-6.2 - -4.7*
Peak -VE time of propulsion	*Mean (SD) (°)*	*63.4 (1.8)*	*63.9 (1.8)*	*45.8 (4.9)*	*46.3 (3.8)*	*58.8 (3.1)*	*60.5 (3.2)*
	95% CI (°)	*63.1 - 63.8*	*63.6 - 64.3*	*44.7 - 46.7*	*45.5- 47.0*	*58.2 - 59.5*	*59.8 - 61.1*
Angle at toe off	Mean (SD) (°)	-17.2 (5.3)	-16.3 (5.2)	6.8 (6.4)	9.1 (5.1)	-1.8 (5.1)	-3.8 (4.5)
	95% CI (°)	*-18.3- -16.1*	*-17.3 - -15.3*	*5.5 - 8.1*	*8.1 - 10.1*	*-2.8- -0.8*	*-4.7 - -2.9*
ROM during swing phase	Mean (SD) (°)	19.5 (5.2)	18.7 (4.3)	-5.1 (7.8)	-7.9 (4.4)	3.6 (8.4)	8.2 (4.7)
	95% CI (°)	*18.4 - 20.5*	*17.8- 19.6*	*-6.7 - -3.5*	*-8.8 - -7.0*	*1.9 - 5.3*	*7.3 - 9.2*
Peak +VE swing phase	*Mean (SD) (°)*	*2.4 (3.7)*	*2.3 (4.5)*	*8.4 (5.3)*	*9.5 (4.8)*	*5.8 (3.5)*	*4.7 (3.5)*
	95% CI (°)	*1.6 - 3.1*	*1.4 - 3.2*	*7.3 - 9.4*	*8.5 - 10.4*	*5.1 - 6.6*	*4.1 - 5.5*
Peak +VE time of swing phase	*Mean (SD) (°)*	*85.8 (2.9)*	*84.5 (2.8)*	*74.3 (11.6)*	*67.2 (6.8)*	*80.6 (6.4)*	*83.8 (5.5)*
	95% CI (°)	*85.3 - 86.4*	*83.9 - 85.1*	*71.9 - 76.6*	*65.9 - 68.6*	*79.3 - 81.8*	*82.7 - 84.9*
Peak -VE swing phase	*Mean (SD) (°)*	*-17.3 (5.2)*	*-16.4 (5.21)*	*-0.3 (4.1)*	*1.0 (3.4)*	*-2.8 (4.3)*	*-4.2 (4.1)*
	95% CI (°)	*-18.3 - -16.3*	*-17.4 - -15.4*	*-1.2 - 0.5*	*0.4 - 1.7*	*-3.7 - -1.9*	*-5.0 - -3.2*
Peak -VE time of swing phase	*Mean (SD) (°)*	*64.1 (2.1)*	*64.4 (1.7)*	*83.5 (6.4)*	*88.6 (7.6)*	*75.5 (11.7)*	*67.2 (7.9)*
	95% CI (°)	*63.7 - 64.5*	*64.0 - 64.7*	*82.2 - 84.8*	*87.1 - 90.1*	*73.2 - 77.8*	*65.9 - 69.1*
Angle at initial heel contact (2)	Mean (SD) (°)	-3.9 (3.9)	-3.5 (4.4)	3.1 (4.3)	2.5 (3.3)	0.6 (3.3)	1.1 (3.1)
	95% CI (°)	*-4.7 - -3.2*	*-2.4 - -2.6*	*2.3 - 3.9*	*1.8 - 3.1*	*-0.1 - 1.2*	*0.51 - 1.8*

Table 6.2 describes the sagittal, frontal and transverse plane kinematic values for the calcaneus relative to the tibia during the gait cycle. Data in grey are considered the primary data.

6.3.2 Midfoot relative to calcaneus

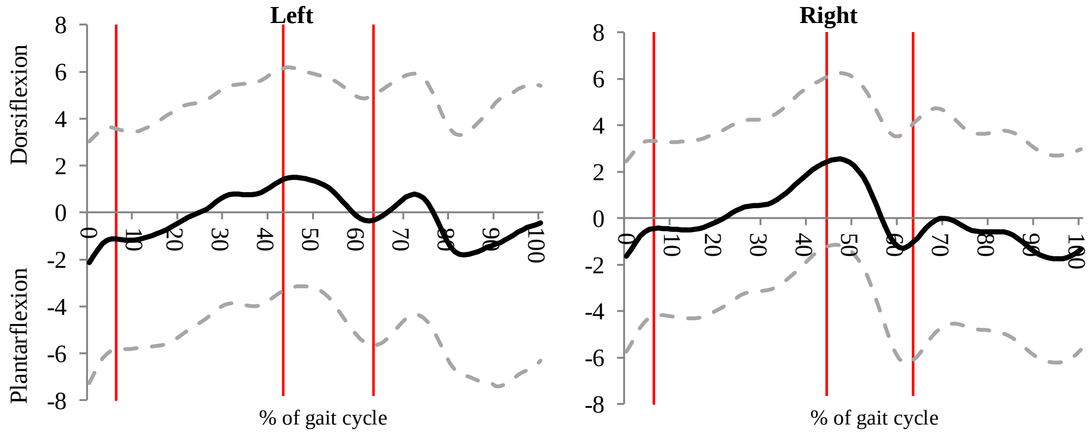


Figure 6.2a (left) and 6.2b (right): Sagittal plane movement of the midfoot relative to the calcaneus during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

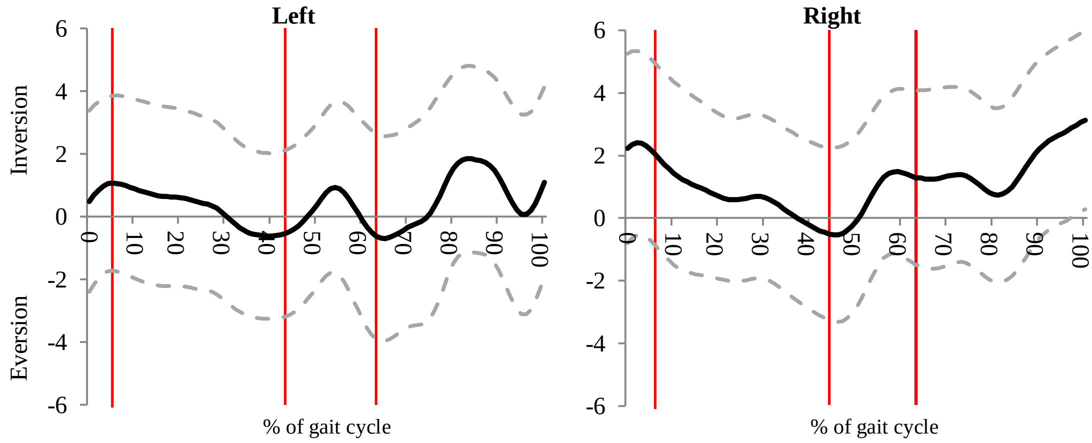


Figure 6.2c (left) and 6.2d (right): Frontal plane movement of the midfoot relative to the calcaneus during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

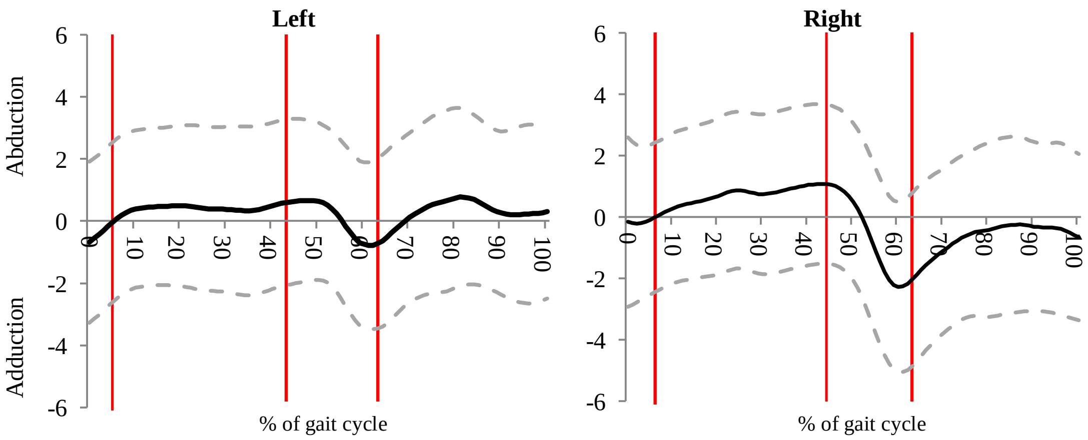


Figure 6.2e (left) and 6.2f (right): Transverse plane movement of the midfoot relative to the calcaneus during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

Contact phase

The midfoot was in a plantarflexed, inverted, and adducted angle relative to the calcaneus at initial heel contact (left: sagittal = -2.1° (SD = 5.1°), frontal = 0.5° (SD = 2.9°), transverse = -0.7° (SD = 2.6°)), and forefoot loading (left: sagittal = -1.2° (SD = 4.7°), frontal = 1.1° (SD = 2.8°), transverse = -0.002° (SD = 2.6°)) (Figures 6.7-6.12). During the contact phase, as demonstrated by Figures 6.2a-6.2f it dorsiflexed (left: 1.3° (SD = 2.3°)) everted (left: -1.3° (SD = 0.8°)) and abducted (left: 0.7° (SD = 1.0°)). There is a similar mean range of motion across all planes of motion, although the standard deviation values indicate some inter-participant variation.

Midstance

During midstance, the midfoot dorsiflexed (left: 5.7° (SD = 2.5°)), everted (left: -2.6° (SD = 2.5°)) and abducted (left: 0.5° (SD = 2.4°)) relative to the calcaneus (Figures 6.2a-6.2f). It was in a dorsiflexed (left: 1.6° (SD = 4.6°)), everted (left: -0.5° (SD = 2.7°)) and abducted (left: 0.6° (SD = 2.6°)) angle at heel lift (Figures 6.2a-6.2f). However, the peak angle of midfoot plantarflexion (left: -2.8° (SD = 4.8°), and inversion (left: 1.9° (SD = 2.7°) relative to the calcaneus during midstance are larger than the angle at forefoot loading. This indicates that the midfoot initially plantarflexed and inverted relative to the calcaneus, and then dorsiflexed and everted during the latter stages of midstance. This is demonstrated by Figures 6.2a-6.2f, but the large inter-participant variation in the direction of motion of the midfoot during this stage does not make this movement clearly identifiable.

Propulsion

During propulsion, the midfoot plantarflexed (left: -2.6° (SD = 5.1°)), everted (left: -0.1 (SD = 3.9°)) and adducted (left: -1.8° (SD = 2.7°)) relative to the calcaneus (Figures 6.2a-6.2f). It was in a plantarflexed (left: -0.5° (SD = 2.7°)), everted (left: -0.5° (SD =3.2°)), or inverted (right: 1.3° (SD = 2.7°)) and adducted (left: -0.8° (SD = 2.7°)) angle at toe off (Figures 6.7-6.12). There is some inter-participant variation in the angle, timing and range of motion of the midfoot relative to the calcaneus. For example, on the left the peak angle of eversion was at 54.4% (SD =7.1%) of the gait cycle, and the peak angle of inversion was at 55.3% (SD = 4.7%) of the gait cycle. Figures 6.2a-6.2f indicate that there is not a consistent pattern between feet in how the midfoot moves during this phase.

Swing phase

During the swing phase, the midfoot plantarflexed (left: -1.8° (SD = 2.7°)), inverted (left: 3.1° (SD = 4.6°)) and abducted (left: 0.5° (SD = 4.0°)) relative to the calcaneus.

Gait Parameter	Descriptive Analysis (+ve angle/ ROM DF,INV,ABD)	(+ve DF, -ve PF) Sagittal (x)		(+ve INV, -ve EVER) Frontal (y)		(+ve ABD, -ve ADD) Transverse (z)	
		Left	Right	Left	Right	Left	Right
Angle at initial heel contact	Mean (SD) (°)	-2.1 (5.1)	-1.6 (4.1)	0.5 (2.9)	2.2 (3.0)	-0.7 (2.6)	-0.2 (2.8)
	95% CI (°)	*-3.2 - -1.1*	*-2.4 - -0.8*	*-0.08 - 1.1*	*1.6 - 2.8*	*-1.2 - -0.2*	*-0.7 - 0.4*
ROM during contact phase	Mean (SD) (°)	1.3 (2.3)	1.5 (1.9)	-1.3 (0.8)	-0.2 (1.8)	0.7 (1.0)	0.2 (1.4)
	95% CI (°)	*0.8 - 1.8*	*1.2 - 1.9*	*-1.5 - -1.1*	*-0.6 - 0.2*	*0.5 - 0.9*	*-0.1 - 0.4*
Peak +VE contact phase	Mean (SD) (°)	-0.5 (4.9)	0.1 (3.8)	1.5 (2.7)	2.9 (2.9)	0.2 (2.6)	0.4 (2.5)
	95% CI (°)	*-1.5 - 0.5*	*0.7 - 0.8*	*0.9 - 2.0*	*2.4 - 3.6*	*-0.3 - 0.7*	*-0.1 - 0.9*
Peak +VE time of contact phase	Mean (SD) (°)	4.4 (1.8)	4.9 (1.8)	4.5 (1.7)	3.5 (1.7)	4.9 (1.9)	3.8 (2.2)
	95% CI (°)	*4.1 - 4.8*	*4.5 - 5.2*	*4.1 - 4.8*	*3.2 - 3.9*	*4.5 - 5.3*	*3.3 - 4.2*
Peak -VE contact phase	Mean (SD) (°)	-2.8 (5.0)	-2.1 (4.1)	0.2 (2.8)	1.4 (2.8)	-0.9 (2.6)	-0.7 (2.6)
	95% CI (°)	*-3.8 - -1.8*	*-2.9 - -1.2*	*-0.4 - 0.8*	*0.8 - 1.9*	*-1.4 - -0.4*	*-1.2 - -0.1*
Peak +VE time of contact phase	Mean (SD) (°)	2.7 (1.7)	2.6 (1.6)	2.8 (1.9)	3.9 (2.5)	2.5 (2.0)	3.8 (1.9)
	95% CI (°)	*2.4 - 3.0*	*2.3 - 2.9*	*2.4 - 3.2*	*3.5 - 4.5*	*2.2 - 2.8*	*3.4 - 4.2*
Angle at forefoot loading	Mean (SD) (°)	-1.2 (4.7)	-0.4 (3.8)	1.1 (2.8)	2.0 (2.9)	-0.002 (2.6)	-0.003 (2.4)
	95% CI (°)	*-2.1 - 0.2*	*-1.2 - 0.4*	*0.5 - 1.6*	*1.5 - 2.6*	*-0.5 - 0.5*	*-0.5 - 0.5*
ROM midstance	Mean (SD) (°)	5.7 (2.5)	4.3 (3.8)	-2.6 (2.5)	-2.8 (3.2)	0.5 (2.4)	1.8 (2.1)
	95% CI (°)	5.2- 6.1	*3.6 - 5.1*	*-3.1 - -2.1*	*-3.5 - -2.2*	*0.02 - 0.9*	*1.4 - 2.2*
Peak +VE midstance	Mean (SD) (°)	2.8 (4.5)	3.4 (3.5)	1.9 (2.7)	2.7 (2.7)	1.5 (2.6)	1.8 (2.6)
	95% CI (°)	*1.9 - 3.7*	*2.7 - 4.1*	*1.4 - 2.5*	*-2.9 - 2.0*	*1.0 - 2.1*	*1.3 - 2.3*
Peak +VE time of midstance	Mean (SD) (°)	30.2 (8.6)	36.9 (9.2)	17.1 (8.8)	16.9 (9.8)	27.6 (9.9)	32.3 (8.1)
	95% CI (°)	*28.4 - 31.9*	*35.1 - 38.9*	*15.4 - 18.9*	*14.9 - 18.9*	*25.6 - 29.6*	*30.6 - 33.9*
Peak -VE midstance	Mean (SD) (°)	-2.8 (4.8)	-1.9 (3.8)	-1.4 (2.7)	-1.2 (2.8)	-0.8 (2.6)	-0.6 (2.5)
	95% CI (°)	*-3.8 - 1.9*	*-2.7 - -1.2*	*-1.9 - -0.9*	*-1.8 - -0.7*	*-1.3 - -0.3*	*-1.1 - 0.1*
Peak -VE time of midstance	Mean (SD) (°)	17.6 (8.4)	19.3 (9.1)	33.1 (8.3)	34.8 (9.6)	22.1 (10.7)	18.6 (9.1)
	95% CI (°)	*15.9 - 19.2*	*17.4 - 21.1*	*31.4 - 34.7*	*32.8 - 36.7*	*19.9 - 24.2*	*16.6 - 20.6*
Angle at heel lift	Mean (SD) (°)	1.6 (4.6)	2.6 ((3.6)	-0.5 (2.7)	-0.4 (2.8)	0.6 (2.6)	0.9 (2.6)
	95% CI (°)	*0.6 - 2.5*	*1.9 - 3.4*	*-1.0 - 0.7*	*-0.9 - 0.2*	*0.1 - 1.1*	*0.4 - 1.9*
ROM propulsion	Mean (SD) (°)	-2.6 (5.1)	-4.7 (4.3)	-0.1 (3.9)	2.6 (2.8)	-1.8 (2.7)	-3.9 (2.2)
	95% CI (°)	*-3.6 - -1.6*	*-5.5 - -3.8*	*-0.9 - 0.7*	*2.1 - 3.2*	*-2.4 - -1.3*	*-4.4 - -3.5*
Peak +VE propulsion	Mean (SD) (°)	3.2 (4.6)	3.5 (3.7)	1.9 (2.6)	2.3 (2.5)	1.4 (2.6)	1.3 (2.6)
	95% CI (°)	*2.3 - 4.1*	*2.8 - 4.3*	*1.4 - 2.4*	*1.8 - 2.9*	*0.8 - 1.9*	*0.8 - 1.8*
Peak +VE time of propulsion	Mean (SD) (°)	51.9 (6.8)	50.3 (4.9)	55.3 (4.7)	58.6 (4.2)	51.7 (5.6)	48.1 (4.3)
	95% CI (°)	*50.6 - 53.3*	*49.3 - 51.3*	*54.3 - 56.2*	*57.7 - 59.4*	*50.6 - 52.8*	*47.2 - 48.9*
Peak -VE propulsion	Mean (SD) (°)	-1.9 (4.9)	-2.2 (4.8)	-1.7 (2.9)	-1.1 (2.8)	-1.5 (2.6)	-2.8 (2.7)
	95% CI (°)	*-2.9 - -0.9*	*-3.2 - -1.2*	*-2.3 - 1.1*	*-1.7 - -0.6*	*-2.0 - -0.9*	*-3.4 - -2.3*
Peak -VE time of propulsion	Mean (SD) (°)	57.9 (5.7)	59.3 (4.8)	54.4 (7.1)	51.1 (5.6)	57.8 (6.5)	60.8 (2.9)
	95% CI (°)	*56.8 - 59.1*	*58.3 - 60.3*	*52.9 - 55.8*	*50.0 - 52.3*	*56.5 - 59.1*	*60.2 - 61.4*
Angle at toe off	Mean (SD) (°)	-0.5 (5.5)	-0.9 (5.2)	-0.5 (3.2)	1.3 (2.7)	-0.8 (2.7)	-2.1 (2.8)
	95% CI (°)	*-1.6 - 0.6*	*-1.9 - 0.1*	*-1.2 - 0.1*	*0.7 - 1.8*	*-1.4 - 0.3*	*-2.7 - -1.6*
ROM swing phase	Mean (SD) (°)	-1.8 (2.7)	-1.3 (5.3)	3.1 (4.6)	2.5 (3.9)	0.5 (4.0)	2.3 (2.9)
	95% CI (°)	*-2.4 - -1.3*	*-2.4 - -0.2*	*2.1 - 4.0*	*1.7 - 3.3*	*-0.3 - 1.3*	*1.7 - 2.9*
Peak +VE swing phase	Mean (SD) (°)	2.9 (5.5)	1.6 (4.4)	3.2 (2.9)	3.8 (2.7)	2.0 (3.0)	0.9 (2.7)
	95% CI (°)	*1.8 - 4.1*	*0.7 - 2.5*	*2.6 - 3.8*	*3.2 - 4.3*	*1.4 - 2.6*	*0.3 - 1.4*
Peak +VE time of swing phase	Mean (SD) (°)	80.5 (11.3)	79.9 (8.8)	84.4 (7.0)	90.6 (9.5)	83.8 (7.9)	86.2 (6.1)
	95% CI (°)	*78.1 - 82.8*	*77.2 - 80.8*	*82.9 - 85.8*	*88.6 - 92.5*	*82.2 - 85.4*	*84.8 - 87.5*
Peak -VE swing phase	Mean (SD) (°)	-4.3 (5.7)	-3.5 (4.5)	-2.1 (3.1)	-0.5 (2.8)	-1.7 (2.5)	-2.6 (2.8)
	95% CI (°)	*-5.5 - -3.1*	*-4.4 - -2.5*	*-2.7 - -1.4*	*-1.1 - 0.9*	*-2.2 - -1.2*	*-3.2 - 2.0*
Peak -VE time of swing phase	Mean (SD) (°)	83.6 (8.9)	84.2 (10.6)	76.8 (9.0)	77.1 (6.9)	79.4 (12.3)	74.1 (10.9)
	95% CI (°)	*81.8 - 85.4*	*82.1 - 86.4*	*74.9 - 78.7*	*75.7 - 78.9*	*76.9 - 81.9*	*71.9 - 76.4*
Angle at initial heel contact (2)	Mean (SD) (°)	-0.5 (5.8)	-1.3 (4.3)	1.1 (3.1)	3.1 (2.9)	0.3 (2.8)	-0.6 (2.7)
	95% CI (°)	*-1.7 - 0.7*	*-2.2 - -0.4*	*0.5- 1.7*	*2.5 - 3.7*	*-0.2 - 0.9*	*-1.2 - -0.1*

Table 6.3 describes the sagittal, frontal and transverse kinematic values for the midfoot relative to the calcaneus during the gait cycle. Data in grey are considered the primary data.

6.3.3 Lateral forefoot relative to the midfoot

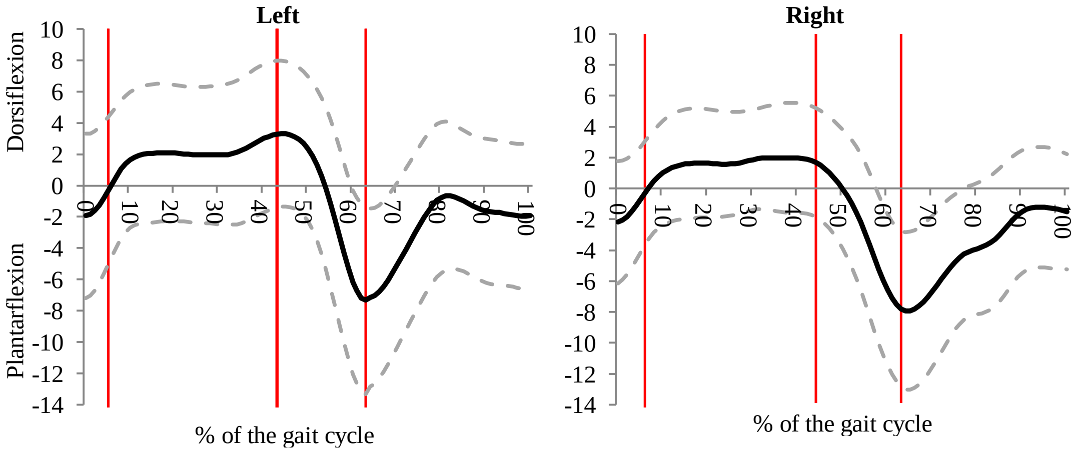


Figure 6.3a (left) and 6.3b (right): Sagittal plane movement of the lateral forefoot relative to the midfoot during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

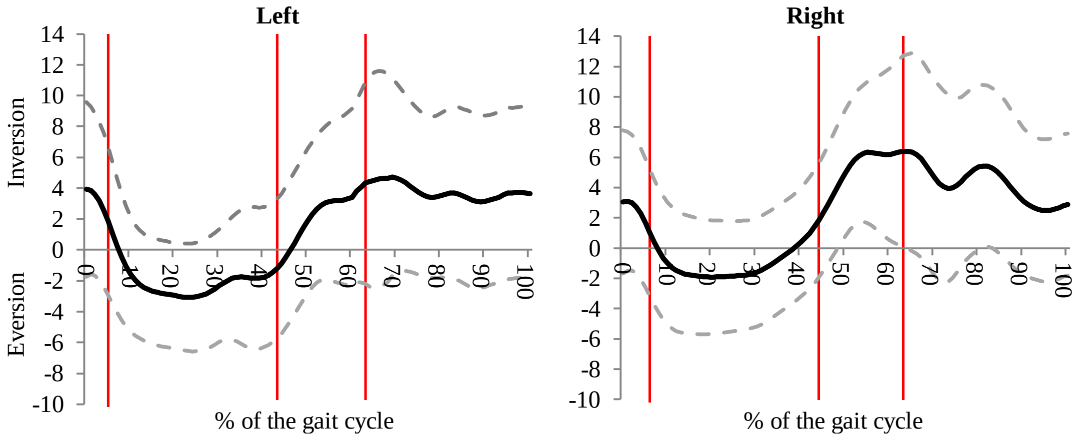


Figure 6.3c (left) and 6.3d (right): Frontal plane movement of the lateral forefoot relative to the midfoot during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

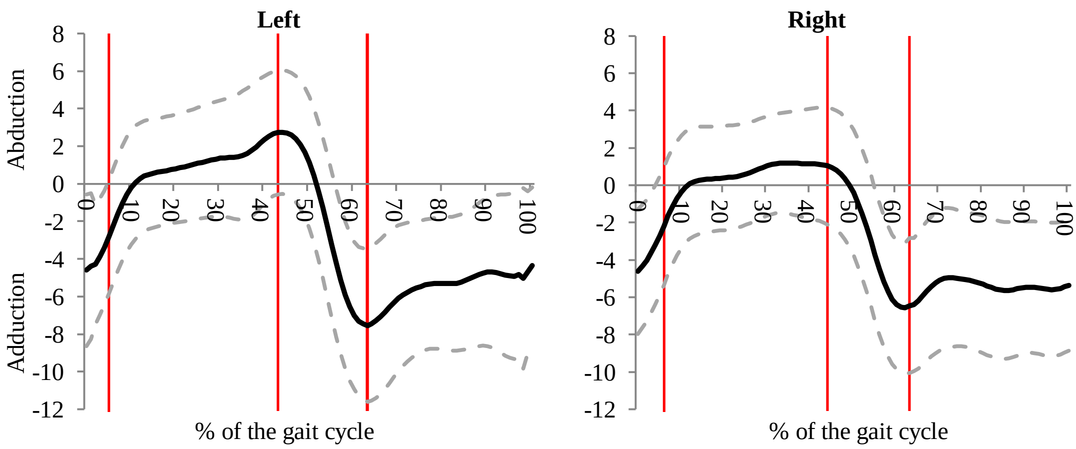


Figure 6.3e (left) and 6.3f (right): Transverse plane movement of the lateral forefoot relative to the midfoot during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off

Contact phase

The lateral forefoot was in a plantarflexed, inverted and adducted angle relative to the midfoot at initial heel contact (left: sagittal = -1.9° (SD = 5.3°), frontal = 3.9° (SD = 5.7°), transverse = -4.6° (SD = 4.0°)), and forefoot loading (left: sagittal = -0.2° (SD = 4.6°), frontal = 1.5° (SD = 4.8°), transverse = -2.6° (SD = 3.0°)) (Figures 6.13-6.18). During the contact phase, as demonstrated by Figures 6.3a-6.3f it dorsiflexed (left: 2.2° (SD = 2.7°)), everted (left: -3.2° (SD = 3.7°)) and abducted (left: 2.7° (SD = 2.8°)).

Midstance

During midstance, the lateral forefoot dorsiflexed (left: 4.1° (SD = 5.2°)), everted (left: -2.8° (SD = 9.6°)) or inverted (right: 3.6° (SD = 6.4°)) and abducted (left: 6.1° (SD = 3.1°)) relative to the midfoot (Figures 6.3a-6.3f). It was in a dorsiflexed (left: 3.3° (SD = 4.8°)), everted (left: -0.8° (SD = 4.5°)) or inverted (right: 2.4° (SD = 3.9°)) and abducted (left: 2.6° (SD = 3.2°)) angle at heel lift (Figures 6.3a-6.3f). For the range of frontal plane motion during this phase, the standard deviation values (left: SD = 9.6°), right: SD = 6.4°)) indicate large inter-participant variation in the range and direction of motion. This may explain the difference between the right and left feet for both of these gait parameters.

Propulsion

From heel lift, the lateral forefoot plantarflexed (left: -11.6° (SD = 4.7°)), inverted (left: 5.8° (SD =7.9°)) and adducted (left: -11.2° (SD = 3.2°)) relative to the midfoot during propulsion (Figures 6.3a-6.3f). It was in a plantarflexed (left: -7.7° (SD = 5.9°)), inverted (left: 4.1° (SD = 6.4°)) and adducted (left: -7.7° (SD = 4.0°)) angle at toe off (Figures 6.3a-6.3f). There is a consistent pattern in the timing of sagittal and transverse plane motion during this phase. For example, as indicated by Figures 6.13-6.18 the peak angle of lateral forefoot dorsiflexion (47.4% (SD = 4.6%)), and abduction (46.1% (SD = 3.2%)) appear to occur at the same time. Later during this phase the peak angle of plantarflexion (62.6% (SD = 3.4)) and adduction (62.4% (SD = 2.3%)) also appear to occur at the same time. All values reported here are on the left, a similar pattern was observed on the left

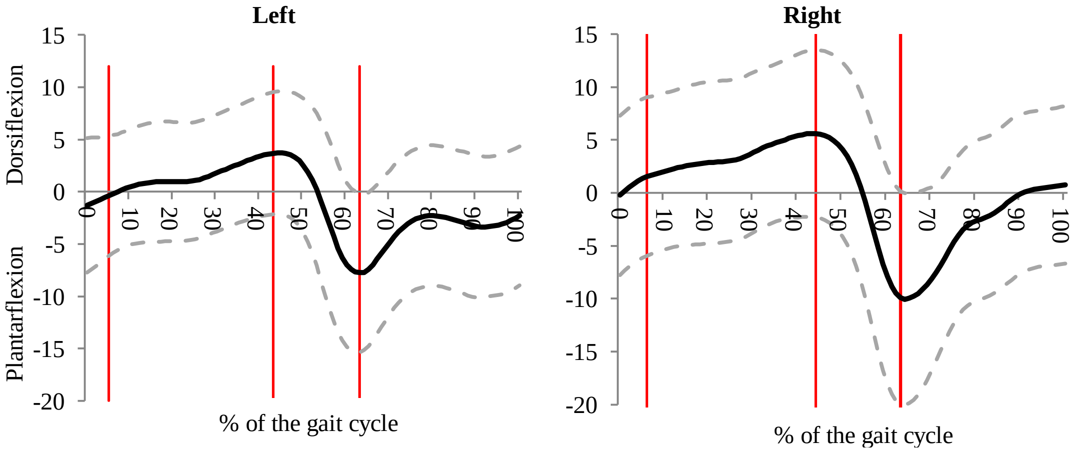
Swing phase

During the swing phase, the lateral forefoot dorsiflexed (left: 7.8° (SD = 5.5°)), everted (left: -2.8° (SD =10.9°)), and abducted (left: 4.0° (SD = 5.6°)) relative to the midfoot. There is relatively consistent inter-participant variation in the range of sagittal and transverse plane motion during this phase.

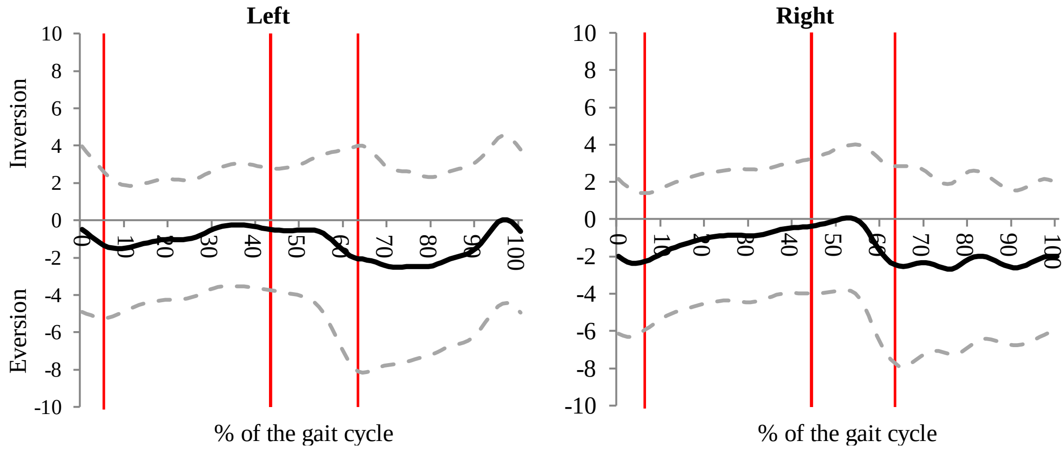
Gait Parameter	Descriptive Analysis (+ve angle/ ROM DF, INV, ABD)	(+ve DF, -ve PF) Sagittal (x) Left	Right	(+ve INV, -ve EVER) Frontal (y) Left	Right	(+ve ABD, -ve ADD) Transverse (z) Left	Right
Angle at initial heel contact	Mean (SD) (°)	-1.9 (5.3)	-2.2 (4.0)	3.9 (5.7)	3.1 (4.7)	-4.6 (4.0)	-4.6 (3.3)
	95% CI (°)	*-3.0 - -0.9*	*-3.0 - -1.3*	*2.8 - 5.1*	*2.0 - 4.1*	*-5.4 - -3.8*	*-5.3 - -3.9*
ROM during contact phase	Mean (SD) (°)	2.2 (2.7)	1.9 (1.8)	-3.2 (3.7)	-1.9 (2.9)	2.7 (2.8)	2.4 (1.0)
	95% CI (°)	*1.6 - 2.7*	*1.5 - 2.3*	*-4.0 - -2.5*	*-2.6 - -1.3*	*2.1 - 3.2*	*2.2 - 2.7*
Peak +VE contact phase	Mean (SD) (°)	0.4 (4.7)	-0.2 (3.7)	4.9 (5.3)	3.9 (4.5)	-2.2 (3.9)	-2.3 (3.4)
	95% CI (°)	*-0.6 - 1.4*	*-1.0 - 0.6*	*3.9 - 6.1*	*2.9 - 4.8*	*-2.9 - 1.4*	*-3.0 - -1.7*
Peak +VE time contact phase	Mean (SD) (°)	5.0 (1.7)	5.5 (1.8)	2.6 (1.4)	2.7 (1.7)	5.5 (1.5)	6.1 (1.6)
	95% CI (°)	*4.7 - 5.4*	*5.1 - 5.8*	*2.3 - 2.9*	*2.3 - 3.0*	*5.2 - 5.8*	*5.8 - 6.5*
Peak -VE contact phase	Mean (SD) (°)	-2.5 (5.1)	-2.5 (3.8)	0.5 (4.8)	0.7 (4.1)	-5.1 (3.3)	-4.8 (3.3)
	95% CI (°)	*-3.6 - -1.5*	*-3.3 - -1.7*	*-0.4 - 1.5*	*-0.1 - 1.6*	*5.8 - 4.4*	*-5.5 - -4.1*
Peak +VE time contact phase	Mean (SD) (°)	2.5 (1.5)	2.3 (1.6)	5.0 (1.7)	5.2 (2.0)	2.1 (1.2)	1.6 (1.3)
	95% CI (°)	*2.2 - 2.8*	*1.9 - 2.6*	*4.6 - 5.4*	*4.8 - 5.7*	*1.9 - 2.3*	*1.4 - 1.9*
Angle at forefoot loading	Mean (SD) (°)	-0.2 (4.6)	-0.5 (3.8)	1.5 (4.8)	1.3 (4.0)	-2.6 (3.0)	-2.5 (3.5)
	95% CI (°)	*-1.2 - 0.7*	*-1.3 - 0.3*	*0.6 - 2.5*	*0.5 - 2.2*	*-3.2 - -1.9*	*-3.2 - -1.8*
ROM midstance	Mean (SD) (°)	4.1 (5.2)	3.3 (4.7)	-2.8 (9.6)	3.6 (6.4)	6.1 (3.1)	4.4 (2.1)
	95% CI (°)	*3.0 - 5.1*	*2.3 - 4.3*	*-4.8 - -0.9*	*2.2 - 4.9*	*5.5 - 6.5*	*3.9 - 4.9*
Peak +VE midstance	Mean (SD) (°)	4.8 (4.6)	4.6 (3.5)	3.4 (4.1)	3.5 (3.8)	3.4 (3.1)	2.1 (2.9)
	95% CI (°)	*3.9 - 5.8*	*3.3 - 4.7*	*2.6 - 4.2*	*2.7 - 4.3*	*2.8 - 4.0*	*1.5 - 2.7*
Peak +VE time midstance	Mean (SD) (°)	32.1 (10.0)	32.3 (9.2)	20.2 (11.8)	30.8 (13.8)	37.5 (7.3)	32.8 (8.6)
	95% CI (°)	*30.0 - 34.1*	*30.3 - 34.2*	*17.8 - 22.7*	*27.9 - 33.8*	*35.9 - 38.9*	*30.9 - 34.7*
Peak -VE midstance	Mean (SD) (°)	-1.3 (4.4)	-1.3 (3.1)	-5.7 (4.3)	-3.5 (3.6)	-2.9 (3.2)	-2.6 (3.1)
	95% CI (°)	*-2.2 - -0.4*	*-2.0 - 0.6*	*-6.6 - -4.8*	*-4.3 - -2.7*	*-3.7 - -2.3*	*-3.2 - -1.9*
Peak -VE time midstance	Mean (SD) (°)	15.7 (9.1)	18.6 (11.7)	26.7 (7.9)	24.7 (6.0)	10.8 (7.3)	9.6 (6.6)
	95% CI (°)	*13.9- 17.6*	*16.1- 21.1*	*25.1- 28.2*	*23.4- 25.9*	*9.1- 12.2*	*8.2- 11.0*
Angle at heel lift	Mean (SD) (°)	3.3 (4.8)	1.5 (3.5)	-0.8 (4.5)	2.4 (3.9)	2.6 (3.2)	0.9 (3.2)
	95% CI (°)	*2.3 - 4.2*	*0.77 - 2.3*	*-1.8 - 0.1*	*1.5 - 3.2*	*1.9 - 3.3*	*0.3 - 1.6*
ROM propulsion	Mean (SD) (°)	-11.6 (4.7)	-9.9 (4.5)	5.8 (7.9)	4.7 (4.8)	-11.2 (3.2)	-8.2 (2.4)
	95% CI (°)	*-12.5 - -10.6*	*-10.8 - -8.9*	*4.2 - 7.4*	*3.2- 6.3*	*-11.9 - -10.5*	*-8.8 - -7.7*
Peak +VE propulsion	Mean (SD) (°)	3.9 (4.4)	1.0 (3.7)	6.2 (5.0)	9.2 (5.1)	3.1 (3.2)	1.1 (3.3)
	95% CI (°)	*3.1 - 4.9*	*1.1 - 2.7*	*5.2 - 7.2*	*8.1 - 10.3*	*2.4 - 3.8*	*0.4 - 1.8*
Peak +VE time propulsion	Mean (SD) (°)	47.4 (4.6)	47.3 (4.8)	58.3 (4.7)	58.2 (4.6)	46.1 (3.2)	46.6 (4.1)
	95% CI (°)	*46.5 - 48.4*	*46.3 - 48.3*	*57.3 - 59.2*	*57.2 - 59.2*	*45.4 - 46.8*	*45.7 - 47.4*
Peak -VE propulsion	Mean (SD) (°)	-7.6 (6.1)	-6.3 (6.2)	-2.7 (5.3)	1.2 (4.2)	-8.1 (0.4)	-7.1 (3.2)
	95% CI (°)	*-8.9- -6.4*	*-7.7 - -5.0*	*-3.8 - -1.0*	*0.3 - 2.1*	*-8.9 - -7.3*	*-7.8 - 6.5*
Peak -VE time propulsion	Mean (SD) (°)	62.6 (3.4)	62.8 (2.6)	49.5 (7.3)	50.7 (8.0)	62.4 (2.3)	61.8 (2.4)
	95% CI (°)	*61.9 - 63.2*	*62.2 - 63.4*	*47.9 - 50.9*	*49.0 - 52.4*	*61.9 - 62.9*	*61.3 - 62.3*
Angle at toe off	Mean (SD) (°)	-7.7 (5.9)	-7.9 (5.2)	4.1 (6.4)	6.3 (6.2)	-7.7 (4.0)	-6.6 (3.5)
	95% CI (°)	*-8.9 - -6.5*	*-9.0 - -6.8*	*2.7 - 5.4*	*5.0 - 7.7*	*-8.5 - -6.9*	*-7.3 - -5.8*
ROM during swing phase	Mean (SD) (°)	7.8 (5.5)	8.6 (3.3)	-2.8 (10.9)	-4.6 (10.1)	4.0 (5.6)	1.5 (4.1)
	95% CI (°)	*6.6 - 9.0*	*7.9 - 9.3*	*-5.2 - -0.4*	*-6.3 - -1.9*	*2.8 - 5.3*	*0.7 - 2.4*
Peak +VE swing phase	Mean (SD) (°)	1.1 (4.9)	-0.1 (3.8)	8.5 (5.2)	9.3 (5.8)	-2.8 (3.7)	-3.5 (3.6)
	95% CI (°)	*-0.4 - 2.1*	*-0.9 - 0.7*	*7.4 - 9.7*	*8.2 - 10.5*	*-3.7 - -2.0*	*-4.3 - -2.8*
Peak +VE time swing phase	Mean (SD) (°)	87.4 (6.8)	92.1 (6.2)	79.2 (8.9)	75.9 (8.5)	88.6 (8.4)	81.6 (9.8)
	95% CI (°)	*89.9 - 88.9*	*90.8 - 93.4*	*77.2 - 81.1*	*74.1 - 77.7*	*86.7 - 90.4*	*79.6 - 83.5*
Peak -VE swing phase	Mean (SD) (°)	-7.9 (5.6)	-8.9 (4.9)	-1.4 (6.7)	-0.2 (5.9)	-8.9 (4.6)	-7.7 (3.5)
	95% CI (°)	*-9.2 - -6.7*	*-9.9 - -7.8*	*-2.9 - 0.1*	*-1.5 - 1.1*	*-9.9 - -7.9*	*-8.4 - -6.9*
Peak -VE time swing phase	Mean (SD) (°)	69.3 (7.5)	67.9 (5.2)	82.4 (9.2)	84.9 (9.4)	72.9 (10.3)	77.2 (11.0)
	95% CI (°)	*67.6 - 70.9*	*66.9 - 69.1*	*80.3 - 84.4*	*82.9 - 86.9*	*70.6 - 75.2*	*74.2 - 79.5*
Angle at initial heel contact (2)	Mean (SD) (°)	-1.9 (4.7)	-1.5 (3.7)	3.6 (5.5)	2.9 (4.7)	-4.3 (4.1)	-5.4 (3.5)
	95% CI (°)	*-2.9 - -0.9*	*-2.3 - -0.7*	*2.4 - 4.9*	*1.8 - 3.9*	*-5.3 - -3.4*	*-6.1 - -4.6*

Table 6.4 describes the kinematic values for the lateral forefoot relative to the midfoot during the gait cycle. Data in grey are considered the primary data.

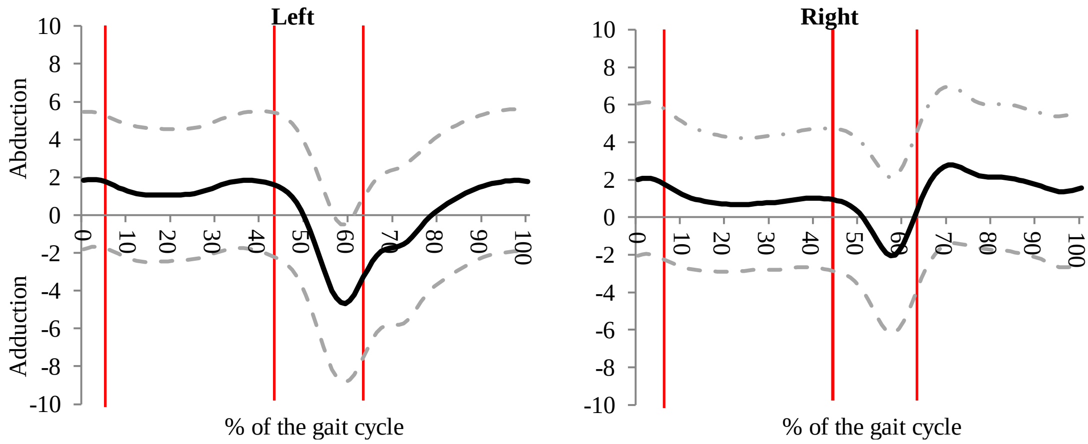
6.3.4 Medial forefoot relative to the midfoot



Figures 6.4a (left) and 6.4b (right): Sagittal plane movement of the medial forefoot relative to the midfoot during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.



Figures 6.4c (left) and 6.4d (right): Frontal plane movement of the medial forefoot relative to the midfoot during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.



Figures 6.4d (left) and 6.4f (right): Transverse plane movement of the medial forefoot relative to the midfoot during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

Contact Phase

The medial forefoot was in a plantarflexed, everted and abducted angle relative to the midfoot at initial heel contact (left: sagittal = -1.3° (SD = 6.4°), frontal = -0.5° (SD = 4.4°), transverse = 1.8° (SD = 3.6°)), and forefoot loading (left: sagittal = -0.5° (SD = 5.6°), frontal = -1.4° (SD = 3.9°), transverse = 1.7° (SD = 3.5°)) (Figures 6.4a-6.4f). During the contact phase, as demonstrated by Figures 6.4a-6.4f it dorsiflexed (left: 0.8° (SD = 2.7°)), or plantarflexed (right: -1.8° (SD = 2.5°)), everted (left: -0.9° (SD = 1.6°)) and adducted (left: -0.3° (SD = 1.1°)). There is greater inter-participant variation in the angle of the medial forefoot relative to the midfoot, than the range of motion during this phase

Midstance

During midstance, the medial forefoot dorsiflexed (left: 5.9° (SD = 3.3°)), inverted (1.4° (SD = 3.7°)) and abducted (left: 0.7° (SD = 2.9°)) or adducted (right: -0.9° (SD = 2.7°)) relative to the midfoot (Figures 6.19-6.24). It was in a dorsiflexed (left: 3.7° (SD = 5.9°)), everted (left: -0.5° (SD = 3.4°)), and abducted (left: 1.6° (SD = 3.7°)) angle at heel lift (Figures 6.4a-6.4f). There was some inter-participant variation during this phase across all planes of motion. In the sagittal plane, this was consistent in the direction of motion, while it was less consistent in the frontal and transverse planes.

Propulsion

During propulsion, the medial forefoot plantarflexed (left: -13.5° (SD = 5.1°), everted (left: -1.5° (SD =6.2°)) and adducted (left: -1.5° (SD = 6.2°)) relative to the midfoot (Figures 6.4a-6.4f). It was plantarflexed (left: -8.5° (SD = 7.3°)), everted (left: -1.9° (SD = 6.0°)), and adducted (left: -3.7° (SD = 4.2°)) or abducted (right: 0.3° (SD = 4.2°)) at toe off (Figures 6.4a-6.4f). The range of sagittal plane motion during this phase was considerably greater than in the frontal or transverse planes.

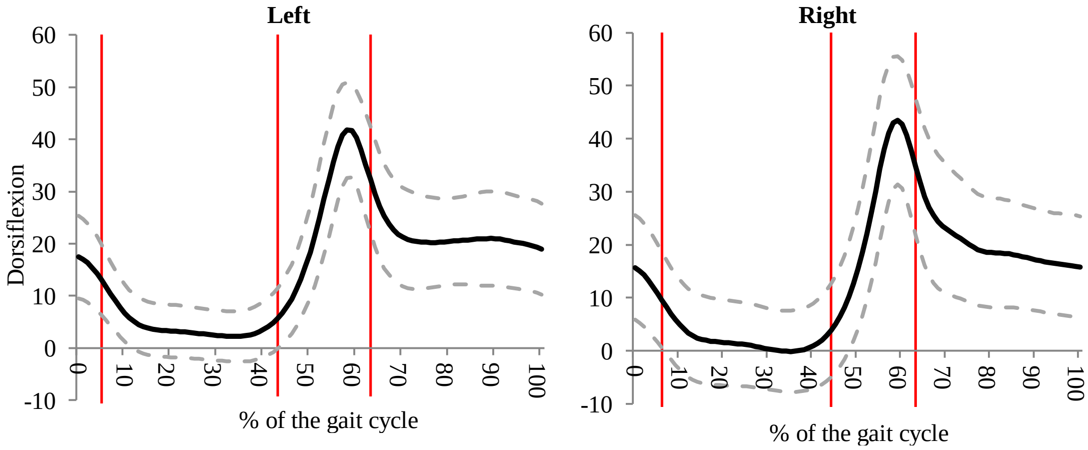
Swing phase

The medial forefoot dorsiflexed (left: 8.2° (SD = 5.9°)), inverted (left: 3.1° (SD= 5.3°)) and abducted (left: 6.5° (SD = 3.2°)) relative to the midfoot during the swing phase.

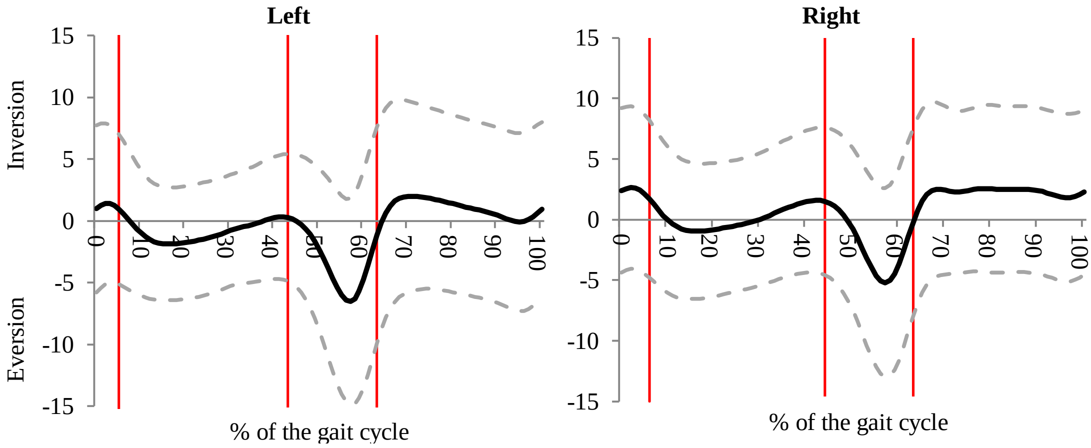
Gait Parameter	Descriptive Analysis (+ve angle/ROM DF, INV,ABD)	(+ve DF, -ve PF) Sagittal (x)		(+ve INV, -ve EVER) Frontal (y)		(+ve ABD, -ve ADD) Transverse (z)	
		Left	Right	Left	Right	Left	Right
Angle at initial heel contact	Mean (SD) (°)	-1.3 (6.4)	-0.2 (7.5)	-0.5 (4.4)	-1.9 (4.2)	1.8 (3.6)	2.0 (4.1)
	95% CI (°)	*-2.6 - -0.01*	*-1.8 - 1.4*	*-1.4 - 0.4*	*-2.9 - -1.1*	*1.1 - 2.6*	*1.2 - 2.9*
ROM contact phase	Mean (SD) (°)	0.8 (2.7)	-1.8 (2.5)	-0.9 (1.6)	-0.2 (1.8)	-0.3 (1.1)	-0.3 (1.2)
	95% CI (°)	*0.3 - 1.3*	*-2.3 - -1.2*	*-1.3 - -0.7*	*-0.6 - 0.2*	*-0.5 - -0.1*	*-0.6 - -0.1*
Peak +VE contact phase	Mean (SD) (°)	0.3 (3.9)	1.9 (7.5)	-0.2 (4.2)	-1.3 (3.9)	2.3 (3.6)	2.5 (4.1)
	95% CI (°)	*-0.9 - 1.5*	*0.3 - 3.4*	*-0.9- -0.6*	*-2.1 - -0.5*	*1.6 - 3.0*	*1.6 - 3.3*
Peak +VE time contact phase	Mean (SD) (°)	4.1 (1.9)	4.9 (2.0)	2.8 (2.0)	3.7 (2.5)	3.5 (1.7)	3.4 (1.7)
	95% CI (°)	*3.7 - 4.5*	*4.5 - 5.3*	*2.4 - 3.1*	*3.2 - 4.1*	*3.1 - 3.8*	*3.1 - 3.8*
Peak -VE contact phase	Mean (SD) (°)	-2.1 (6.1)	0.7 (7.4)	-1.7 (4.1)	-2.9 (3.9)	1.3 (3.5)	1.4 (3.9)
	95% CI (°)	*-3.3 - -0.9*	*-2.3 - 0.9*	*-2.5 - -0.8*	*-3.8 - -2.1*	*0.6 - 1.9*	*0.6 - 2.2*
Peak +VE time contact phase	Mean (SD) (°)	3.2 (2.0)	2.9 (2.2)	4.6 (1.8)	3.9 (1.9)	4.0 (2.0)	4.4 (2.3)
	95% CI (°)	*2.8 - 3.6*	*2.5 - 3.4*	*4.2 - 4.9*	*3.6 - 4.4*	*3.6 - 4.4*	*3.9 - 4.8*
Angle at forefoot loading	Mean (SD) (°)	-0.5 (5.6)	1.3 (7.5)	-1.4 (3.9)	-2.2 (3.7)	1.7 (3.5)	1.8 (4.0)
	95% CI (°)	*-1.6 - 0.6*	*-0.3 - 2.9*	*-2.1 - 0.6*	*-2.9 - -1.4*	*0.9 - 2.4*	*0.9 - 2.6*
ROM midstance	Mean (SD) (°)	5.9 (3.3)	5.8 (4.8)	1.4 (3.7)	2.5 (3.5)	0.7 (2.9)	-0.9 (2.7)
	95% CI (°)	*5.2 - 6.6*	*4.8 - 6.7*	*0.6 - 2.1*	*1.7 - 3.2*	*0.1 - 1.2*	*-1.5 - -0.3*
Peak +VE midstance	Mean (SD) (°)	4.7 (5.8)	6.9 (7.8)	0.9 (3.2)	0.7 (3.5)	2.9 (3.6)	2.4 (3.9)
	95% CI (°)	*3.5 - 5.8*	*5.3 - 8.6*	*0.2 - 1.5*	*0.01 - 1.5*	*2.2 - 3.6*	*1.6 - 3.2*
Peak +VE time midstance	Mean (SD) (°)	35.4 (8.6)	37.7 (8.4)	28.6 (11.1)	31.6 (9.7)	26.9 (12.6)	21.6 (12.4)
	95% CI (°)	*33.6 - 37.1*	*35.9 - 39.4*	*26.3 - 30.8*	*29.6 - 37.7*	*24.4 - 29.5*	*18.9 - 24.8*
Peak -VE midstance	Mean (SD) (°)	-1.6 (5.7)	0.2 (7.2)	-2.8 (3.5)	-3.2 (3.4)	0.1 (3.5)	-0.3 (3.7)
	95% CI (°)	*-2.7 - -0.5*	*-1.3 - -1.7*	*-3.5 - -2.1*	*-3.9 - -2.5*	*-0.6 - 0.8*	*-0.9 - 0.5*
Peak -VE time midstance	Mean (SD) (°)	14.9 (7.3)	15.4 (8.5)	19.6 (11.0)	18.8 (10.5)	24.5 (9.8)	28.8 (9.5)
	95% CI (°)	*13.4 - 16.3*	*13.6 - 17.1*	*17.4 - 21.8*	*16.6 - 21.0*	*22.3 - 26.4*	*26.8 - 30.8*
Angle at heel lift	Mean (SD) (°)	3.7 (5.9)	5.4 (7.7)	-0.5 (3.4)	-0.4 (3.6)	1.6 (3.7)	0.9 (3.8)
	95% CI (°)	*2.5 - 4.8*	*3.8 - 7.0*	*-1.2 - 0.2*	*-1.1 - 0.4*	*0.8 - 2.3*	*0.1 - 1.7*
ROM propulsion	Mean (SD) (°)	-13.5 (5.1)	-16.7 (7.8)	-1.5 (6.2)	-2.7 (6.3)	-1.5 (6.2)	-1.3 (5.1)
	95% CI (°)	*-14.5 - -12.5*	*-18.4 - -15.1*	*-2.7 - -0.2*	*-4.0 - -1.4*	*-2.7- -0.2*	*-2.4 - -0.2*
Peak +VE propulsion	Mean (SD) (°)	4.5 (6.0)	6.1 (7.7)	1.6 (4.1)	1.9 (3.8)	1.8 (3.8)	2.1 (3.8)
	95% CI (°)	*3.3 - 5.7*	*4.4 - 7.7*	*0.8 - 2.5*	*1.2 - 2.8*	*1.0 - 2.5*	*1.3 - 2.9*
Peak +VE time propulsion	Mean (SD) (°)	43.5 (4.1)	48.1 (3.8)	52.7 (6.8)	53.8 (6.6)	46.3 (5.4)	54.0 (8.3)
	95% CI (°)	*46.6 - 48.3*	*47.3 - 48.9*	*51.4 - 54.1*	*52.5 - 55.1*	*45.3 - 47.4*	*52.4 - 55.7*
Peak -VE propulsion	Mean (SD) (°)	-9.0 (7.4)	-11.0 (9.5)	-3.9 (4.6)	-4.2 (4.5)	-5.4 (4.0)	-2.9 (4.0)
	95% CI (°)	*-10.5 - -7.5*	*-13.0 - -9.0*	*-4.9 - -3.0*	*-5.1 - -3.2*	*-6.2 - -4.6*	*-3.7 - -2.0*
Peak -VE time propulsion	Mean (SD) (°)	62.3 (2.6)	62.9 (2.4)	55.6 (8.5)	57.7 (6.8)	59.6 (2.3)	57.6 (3.4)
	95% CI (°)	*61.8 - 62.9*	*62.4 - 63.4*	*53.9 - 57.3*	*58.3 - 59.1*	*59.2 - 60.1*	*56.9 - 58.3*
Angle at toe off	Mean (SD) (°)	-8.5 (7.3)	-10.5 (9.8)	-1.9 (6.0)	-2.5 (5.4)	-3.7 (4.2)	0.3 (4.2)
	95% CI (°)	*-9.9 - -7.1*	*-12.6 - -8.5*	*-3.2 - 0.8*	*-3.6 - -1.3*	*-4.5 - -2.8*	*-0.6- 1.2*
ROM swing phase	Mean (SD) (°)	8.2 (5.9)	13.5 (6.2)	3.1 (5.3)	0.9 (6.1)	6.5 (3.2)	0.8 (4.7)
	95% CI (°)	*7.0 - 9.4*	*12.2 - 14.8*	*2.1 - 4.2*	*-0.4 - 2.2*	*5.9 - 7.2*	*-0.2 - 1.8*
Peak +VE swing phase	Mean (SD) (°)	0.3 (6.5)	1.9 (7.7)	1.3 (5.0)	0.6 (4.4)	2.8 (3.7)	3.9 (4.1)
	95% CI (°)	*-1.0 - 1.6*	*0.3 - 3.6*	*0.3 - 2.3*	*-0.4 - 1.5*	*2.1 - 3.6*	*3.1 - 4.8*
Peak +VE time swing phase	Mean (SD) (°)	86.5 (7.8)	94.4 (6.2)	86.7 (12.0)	8.3 (11.1)	91.9 (7.2)	78.0 (8.0)
	95% CI (°)	*84.9 - 88.1*	*93.2 - 95.7*	*84.2 - 89.1*	*78.9 - 83.6*	*90.4 - 93.4*	*76.3 - 79.7*
Peak -VE swing phase	Mean (SD) (°)	-9.4 (7.2)	-11.8 (9.4)	-4.4 (4.9)	-5.1 (4.6)	-3.9 (4.2)	-0.6 (3.4)
	95% CI (°)	*-10.9 - -7.9*	*-13.8 - -9.8*	*-5.4 - -3.4*	*6.1 - -4.2*	*-4.8 - -3.1*	*-1.4 -0.3*
Peak -VE time swing phase	Mean (SD) (°)	69.1 (8.0)	67.3 (4.0)	76.3 (7.7)	78.1 (10.6)	67.4 (5.6)	76.6 (11.6)
	95% CI (°)	*67. 5- 70.8*	*66.5 - 68.2*	*74.8 - 77.9*	*75.9 - 80.3*	*66.3 - 68.6*	*74.2 - 79.1*
Angle at initial heel contact (2)	Mean (SD) (°)	-2.2 (6.6)	0.9 (7.3)	-0.6 (4.4)	-1.9 (4.0)	1.9 (3.7)	1.7 (4.2)
	95% CI (°)	*-3.5 - -0.8*	*-0.7- 2.4*	*-1.5 - 0.3*	*-2.8 - -1.1*	*1.2 - 2.6*	*0.8 - 2.5*

Table 6.5 describes the kinematic values for the medial forefoot relative to the midfoot during the gait cycle. Data in grey are considered the primary data.

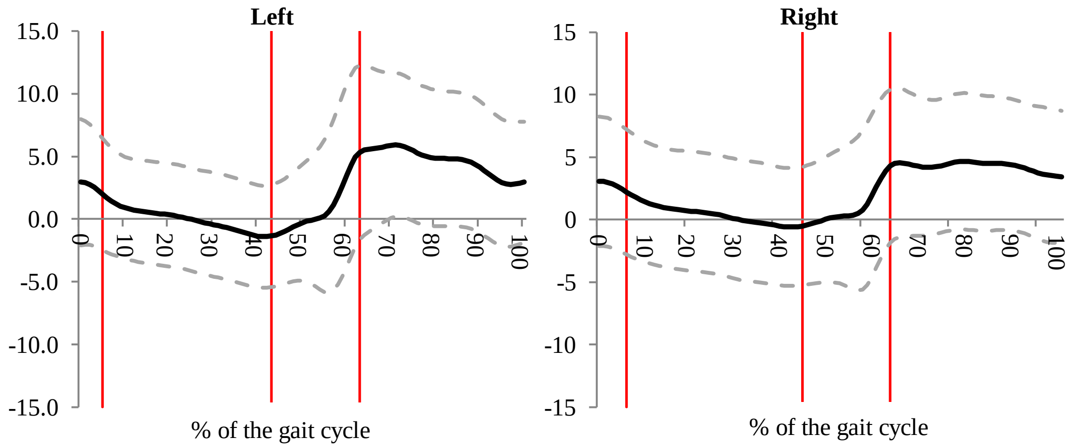
6.3.5 Hallux relative to the medial forefoot



Figures 6.5a (left) and 6.5b (right): Sagittal plane movement of the hallux relative to the medial forefoot during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.



Figures 6.5c (left) and 6.5d (right): Frontal plane movement of the hallux relative to the medial forefoot during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.



Figures 6.5e (left) and 6.5f (right): Transverse plane movement of the hallux relative to the medial forefoot during the gait cycle. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

Contact phase

The hallux was dorsiflexed, inverted and abducted relative to the medial forefoot at initial heel contact (left: sagittal = 17.4° (SD = 7.9°), frontal = 0.9° (SD = 6.8°), transverse = 2.9° (SD = 5.1°)), and forefoot loading (left: sagittal = 12.7° (SD = 6.7°), frontal = 0.9° (SD = 6.0°), transverse = 1.9° (SD = 4.4°)) (Figures 6.5a-6.5f). During the contact phase, as demonstrated by Figures 6.5a-6.5f it plantarflexed (left: -4.9° (SD = 3.6°)), everted (left: -0.6° (SD = 2.2°)), and abducted (left: 1.1° (SD = 1.7°)) or adducted (right: -0.9° (SD = 1.6°)).

Midstance

During midstance, the hallux plantarflexed (left: -9.8° (SD = 9.5°)), everted (left: -0.3° (SD = 6.1°)) or inverted (right: 0.1° (SD = 5.7°)), and adducted (left: -3.9° (SD = 2.9°)) relative to the medial forefoot (Figures 6.5a-6.5f). It is in a dorsiflexed (left: 6.1° (SD =5.3°)), inverted (left: 0.01° (SD = 5.2°)), and abducted (left: 1.2° (SD = 4.2°)) or adducted (right: -0.4° (SD = 4.9°)) angle at heel lift (Figures 6.5a-6.5f). As similar to the contact phase, the range of sagittal plane motion is much greater than the range of frontal and transverse plane motion. There is a much greater consistency between participants in the direction of motion in the sagittal plane. In the frontal and transverse planes, the small mean values and large standard deviation values indicate there is not consistency in the direction of motion in these planes.

Propulsion

During propulsion, the hallux dorsiflexed (left: 38.9° (SD =7.3°)), everted (left: -4.0° (SD = 10.6°)), and abducted (left: 7.0° (SD = 6.7°)) relative to the medial forefoot (Figures 6.5a-6.5f). It is in a dorsiflexed (left: 33.2° (SD = 9.8°)), everted (left: -1.7° (SD= 8.7°)) and abducted (left: 5.3° (SD = 6.8°)) angle at toe off (Figures 6.5a-6.5f). The range of, and angle of the hallux relative to the medial forefoot in the sagittal plane is much larger than the range or angle of in the frontal, or transverse planes. Figures 6.5a-6.5f indicates that the pattern of movement in the sagittal plane is much more consistent in the direction of dorsiflexion. There is less consistency in the direction of motion in frontal and transverse planes. The standard deviation curves for these planes of motion intersect both direction of motion in the frontal and transverse plane, but not in the sagittal plane.

Swing phase

During the swing phase , the hallux plantarflexed (left: -16.9° (SD= 7.3°)), inverted (left: 1.6° (SD = 7.3°)), and abducted (left: 3.1° (SD = 9.7°)) relative to the medial forefoot.

Gait Parameter	Descriptive Analysis (+ve angle/ROM DF, INV,ABD)	(+ve DF, -ve PF) Sagittal (x) Left	Right	(+ve INV, -ve EVER) Frontal (y) Left	Right	(+ve ABD, -ve ADD) Transverse (z) Left	Right
Angle at initial heel contact	Mean (SD) (°)	17.4 (7.9)	15.7 (9.9)	0.9 (6.8)	2.4 (6.8)	2.9 (5.1)	3.1 (5.2)
	95% CI (°)	*15.9 - 19.0*	*13.7 - 17.7*	*-0.4 - 2.3*	*1.0 - 3.8*	*1.9 - 3.9*	*1.9 - 4.1*
ROM contact phase	Mean (SD) (°)	-4.9 (3.6)	-5.7 (3.8)	-0.6 (2.2)	-0.7 (2.2)	1.1 (1.7)	-0.9 (1.6)
	95% CI (°)	*-5.7- -4.3*	*-4.9 - -6.4*	*-1.0 - -1.4*	*-1.1 - -0.3*	*0.8 - 1.4*	*-1.2 - -0.5*
Peak +VE contact phase	Mean (SD) (°)	17.8 (7.9)	15.9 (9.8)	2.0 (6.3)	3.2 (6.8)	3.3 (5.0)	3.5 (5.1)
	95% CI (°)	*16.2 - 19.4*	*13.9 - 17.9*	*0.8 - 3.3*	*1.8 - 4.5*	*2.3 - 4.3*	*2.4 - 4.5*
Peak +VE time contact phase	Mean (SD) (°)	1.9 (1.2)	1.5 (1.0)	3.4 (1.7)	3.3 (1.7)	2.5 (1.8)	2.9 (1.8)
	95% CI (°)	*1.7 - 2.2*	*1.3 - 1.7*	*3.1 - 3.7*	*2.9 - 3.6*	*2.2 - 2.9*	*2.5 - 3.3*
Peak -VE contact phase	Mean (SD) (°)	12.5 (6.6)	10.1 (9.1)	0.1 (6.4)	1.2 (6.5)	1.6 (4.4)	1.9 (5.1)
	95% CI (°)	*11.2 - 13.8*	*8.2 - 11.9*	*-1.2 - 1.4*	*-0.1 - 2.5*	*0.8 - 2.5*	*0.9 - 2.9*
Peak +VE time contact phase	Mean (SD) (°)	5.7 (1.5)	6.4 (1.6)	4.1 (2.1)	4.7 (2.3)	4.9 (2.0)	4.9 (2.0)
	95% CI (°)	*5.4- 6.1*	*6.1- 6.7*	*3.7- 4.5*	*4.2- 5.2*	*4.5- 5.3*	*4.5- 5.3*
Angle at forefoot loading	Mean (SD) (°)	12.7 (6.7)	10.2 (9.1)	0.9 (6.0)	1.8 (6.4)	1.9 (4.4)	2.3 (4.0)
	95% CI (°)	*11.4 - 14.1*	*8.4 - 12.1*	*-0.3 - 2.1*	*0.5 - 3.1*	*1.1 - 2.8*	*1.3 - 3.3*
ROM midstance	Mean (SD) (°)	-9.8 (9.5)	-8.9 (10.5)	-0.3 (6.1)	0.1 (5.7)	-3.9 (2.9)	-3.4 (3.5)
	95% CI (°)	*-11.7 - -7.9*	*-11.1 - -6.9*	*-1.5 - 0.9*	*-1.1 - 1.2*	*-4.5 - -3.3*	*-4.1 - -2.7*
Peak +VE midstance	Mean (SD) (°)	13.4 (6.1)	11.6 (7.7)	2.6 (5.5)	3.3 (5.7)	2.5 (4.4)	3.3 (5.2)
	95% CI (°)	*12.1 - 14.6*	*10.1 - 13.2*	*1.5 - 3.7*	*2.1 - 4.4*	*1.6 - 3.3*	*2.3 - 4.3*
Peak +VE time midstance	Mean (SD) (°)	12.6 (10.3)	15.4 (11.5)	22.8 (14.0)	25.3 (14.9)	12.7 (7.8)	14.4 (10.6)
	95% CI (°)	*10.5 - 14.6*	*13.0 - 17.7*	*20.0 - 25.6*	*22.9 - 28.3*	*11.1 - 14.2*	*12.2 - 16.5*
Peak -VE midstance	Mean (SD) (°)	0.5 (4.6)	-1.3 (6.7)	-2.9 (4.7)	-2.1 (5.7)	-1.9 (3.9)	-1.1 (4.8)
	95% CI (°)	*-0.4 - 1.4*	*-2.7 - -0.01*	*-3.8 - -1.9*	*-3.2 - -0.9*	*-2.8 - 1.2*	*-2.0 - -0.1*
Peak -VE time midstance	Mean (SD) (°)	29.4 (7.2)	30.5 (7.0)	22.1 (9.4)	22.5 (9.1)	36.1 (8.4)	35.5 (9.3)
	95% CI (°)	*27.9 - 30.8*	*29.1 - 31.9*	*20.2 - 24.0*	*20.7 - 24.4*	*34.4 - 37.8*	*33.6 - 37.4*
Angle at heel lift	Mean (SD) (°)	6.1 (5.3)	4.9 (8.0)	0.01 (5.2)	1.0 (6.1)	1.2 (4.0)	-0.4 (4.9)
	95% CI (°)	*5.1 - 7.2*	*3.3 - 6.5*	*-1.0 - 1.0*	*-0.2 - 2.2*	*-2.0 - -0.4*	*-1.4 - 0.6*
ROM propulsion	Mean (SD) (°)	38.9 (7.3)	42.1 (8.7)	-4.0 (10.6)	-3.9 (9.9)	7.0 (6.7)	5.8 (6.2)
	95% CI (°)	*37.5 - 40.4*	*40.4 - 43.9*	*-6.2 - -1.9*	*-5.9 - -1.9*	*5.7 - 8.4*	*4.6 - 7.1*
Peak +VE propulsion	Mean (SD) (°)	44.9 (8.7)	46.9 (11.8)	2.4 (6.4)	3.1 (6.3)	6.1 (6.4)	5.6 (6.9)
	95% CI (°)	*43.3 - 46.7*	*44.6 - 49.4*	*1.1 - 3.7*	*1.8 - 4.4*	*4.8 - 7.3*	*4.2 - 7.0*
Peak +VE time propulsion	Mean (SD) (°)	59.9 (2.0)	59.9 (1.9)	52.4 (8.9)	53.4 (7.7)	60.4 (5.6)	60.6 (5.2)
	95% CI (°)	*59.0 - 59.8*	*59.6 - 60.4*	*50.6 - 54.2*	*51.9 - 54.9*	*59.3 - 61.5*	*59.6 - 61.7*
Peak -VE propulsion	Mean (SD) (°)	6.1 (5.3)	4.9 (8.0)	-7.9 (8.2)	-6.8 (7.6)	-2.8 (5.2)	-1.9 (5.4)
	95% CI (°)	*5.0 - 7.2*	*3.2 - 6.5*	*-9.5 - -6.3*	*-8.3 - -5.1*	*-3.9 - -1.8*	*-3.1 - -0.9*
Peak -VE time propulsion	Mean (SD) (°)	43.8 (4.7)	45.7 (4.3)	56.4 (5.2)	56.9 (5.3)	49.9 (6.5)	52.2 (6.2)
	95% CI (°)	*42.9 - 44.7*	*44.8 - 46.6*	*55.3 - 57.3*	*55.8 - 57.9*	*48.6 - 51.2*	*50.9 - 53.4*
Angle at toe off	Mean (SD) (°)	33.2 (9.8)	34.9 (13.1)	-1.7 (8.7)	-0.1 (7.6)	5.3 (6.8)	4.4 (6.3)
	95% CI (°)	*31.2 - 35.1*	*32.2 - 37.5*	*-3.5 - 0.1*	*-1.6 - 1.5*	*3.9 - 6.6*	*3.2 - 5.7*
ROM swing phase	Mean (SD) (°)	-16.9 (7.3)	-21.4 (7.4)	1.6 (7.3)	2.2 (7.3)	3.1 (9.7)	0.4 (7.2)
	95% CI (°)	*-18.4- -15.4*	*-22.9- -19.9*	*0.1- 3.0*	*0.7- 3.7*	*1.1- 5.0*	*-1.1- 1.9*
Peak +VE swing phase	Mean (SD) (°)	33.5 (9.7)	35.1 (12.8)	3.9 (7.5)	5.2 (6.9)	7.5 (5.6)	7.2 (6.2)
	95% CI (°)	*31.6 - 35.5*	*32.4 - 37.7*	*2.3 - 5.4*	*3.8 - 6.7*	*6.4 - 8.7*	*5.9 - 8.5*
Peak +VE time swing phase	Mean (SD) (°)	65.5 (5.4)	65.2 (3.8)	78.7 (8.6)	81.1 (10.9)	73.6 (7.7)	77.9 (9.1)
	95% CI (°)	*64.4 - 66.6*	*64.5 - 65.9*	*76.9 - 80.4*	*78.9 - 83.4*	*72.0 - 75.1*	*76.1 - 79.8*
Peak -VE swing phase	Mean (SD) (°)	15.9 (8.3)	13.6 (9.9)	-3.1 (8.0)	-1.8 (7.0)	-1.8 (5.5)	0.9 (5.6)
	95% CI (°)	*14.2 - 17.5*	*11.6 - 15.7*	*-4.7 - -1.5*	*-3.3 - -0.4*	*-2.9 - -0.7*	*-0.3 - 2.0*
Peak -VE time swing phase	Mean (SD) (°)	86.2 (10.3)	91.6 (7.8)	76.3 (12.4)	75.2 (12.2)	75.3 (12.0)	80.1 (11.3)
	95% CI (°)	*84.1 - 88.3*	*90.0 - 93.1*	*73.8 - 78.8*	*72.7 - 77.7*	*72.9 - 77.7*	*77.8 - 82.4*
Angle at initial heel contact (2)	Mean (SD) (°)	18.9 (8.7)	15.7 (9.6)	0.9 (7.1)	2.4 (6.8)	2.9 (4.9)	3.4 (5.4)
	95% CI (°)	*17.2 - 20.7*	*13.7 - 17.7*	*-0.5 - 2.4*	*0.9 - 3.8*	*1.9 - 3.9*	*2.3 - 4.5*

Table 6.6 describes the kinematic values for the hallux relative to the medial forefoot during the gait cycle. Data in grey are considered the primary data.

6.3.6 Discussion – Inter-segmental angle data

The purpose of reporting this data was to demonstrate the source kinematic data and compare it to the literature that has used similar methods for measuring the kinematic motion of the foot.

Overall the results from this investigation are similar to the kinematic data from other (Leardini et al 2007, Hunt et al 2001a, Simon et al 2006, Carosn et al 2001, Moseley et al 1996, Rattanaprasert et al 1999, Kitaoka et a 2006, DeMits et al 2012, Jenkyn and Nicol 2007, MacWilliams et al 2003, Nester et al 2007) investigations Therefore, indicating it provides as suitable as they provide representation of the kinematic motion within the foot. The results from this and other (Leardini et al 2007, Hunt et al 2001a, Simon et al 2006, Carson et al 2001, Moseley et al 1996, Rattanaprasert et al 1999, Kitaoka et a 2006, DeMits et al 2012, Jenkyn and Nicol 2007, MacWilliams et al 2003, Nester et al 2007, Lundgren et al 2007, Nester et al 2006) investigations also demonstrate that there is motion between all joints of the foot. Therefore, suggesting that all aid the function and movement of the foot, leg and the lower limb during the gait cycle.

For all inter-segmental angles and range of motion calculated within the foot, there was large inter-participant variation across all planes of motion. In the sagittal plane, the variation was consistent in the direction of motion. However, in the frontal and transverse planes there was less consistency in the direction of motion, highlighting the individual variation in how the feet of different people function.

The sagittal plane is the direction in which the largest range of motion occurs at most inter-segmental angles (Leardini et al 2007, Hunt et al 2001a, Kitaoka et a 2006, DeMits et al 2012, Jenkyn and Nicol 2007, MacWilliams et al 2003, Nester et al

2007, Lundgren et al 2007, Nester et al 2006). This indicates that the foot plays a key role in facilitating the movement forwards of the body in the path of directional travel. The dorsiflexion between the calcaneus relative to the tibia during midstance (Hunt et al 2001a, Perry 1992) allows the foot to remain in plantigrade contact with the floor as the tibia and lower limb rotate above it. There was a large range of dorsiflexion at the lateral forefoot relative to the midfoot, medial forefoot relative the midfoot and the hallux relative to the medial forefoot during propulsion. This can be proposed to allow the forefoot to pivot upon it as the heel lifts from the ground and contribute to the forward motion of the body. This and other (Halstead and Redmond 2006, Nawoczenski et al 1999, Van Gheluwe et al 2006, Simon et al 2006, Carson et al 2001 and MacWilliams et al 2003) investigations report that there is large inter-participant variation in the movement of the first metatarsophalangeal joint during walking. However, Hicks (1953), Fuller et al (2000), Bojson-Moller (1979) and Huson (1991) describe how the movement of this joint during is controlled by muscles and tendons that insert near the joint itself This includes the plantar aponeurosis too and the windlass mechanism. Therefore, it is possible that the variation in how these soft tissues function may contribute to the difference between participants.

This investigation and others (Simon et al 2006, Pierrynowski and Smith 1996, Jenkyn and Nicol 2007, Perry 1992) are some of the very few to have measured the kinematic motion of the foot during the swing phase. The primary task during the swing phase is to aid ground clearance which is highlighted by the large range of dorsiflexion between the calcaneus relative to the tibia during the early stages of the swing phase.

Huson (1991), Hunt et al (2001a) and DeMits et al (2012) proposed that there are medial and lateral arches of the foot. These are commonly reported in clinical gait analysis by measuring the lateral forefoot/fifth metatarsal relative to the midfoot/cuboid and the medial forefoot/first metatarsal relative to the midfoot/navicular and or medial cuneiform. Together with the surrounding soft tissue structures, such as the plantar fascia, the many extensor and flexor tendons that insert into the foot and the intrinsic muscles of the foot, these arches provide the structural framework of the foot. These aid the adaptability and stability of the foot so that the lower limb can continue moving forwards above the foot, almost regardless of terrain.

The different kinematic movement patterns of the medial forefoot relative to the midfoot and the lateral forefoot relative to the midfoot in some planes of motion indicate their individual importance in aiding the function of the foot (DeMits et al 2012, MacWilliams et al 2003, Lundgren et al 2007, and Nester et al 2006). For example, this investigation reports that during propulsion the medial forefoot everted and adducted relative to the midfoot during this phase. This movement is described by Huson (1991) as important for maintaining the medial aspect of the forefoot in contact with the supporting surface to help facilitate dorsiflexion at the first metatarsophalangeal joint.

In contrast, the lateral forefoot inverted and abducted relative to the midfoot during propulsion. This was incidentally almost double the range of motion than on the medial aspect of the foot. Huson (1991) suggests that inversion of the lateral forefoot relative to the midfoot is because the calcaneus is inverting relative to the talus during this phase. As the cuboid is anatomically next to the cuboid this will subsequently affect the movement of it which will in-turn affect the movement of the fourth and fifth metatarsals. The movement on the medial side of the foot maybe less because the cuneiforms are between the navicular and metatarsals. Overall, this strongly advocates the division of the forefoot into separate medial and lateral regions rather than as a single rigid segment.

However, the results of this investigation do to some extent support combining the navicular and cuboid together as one rigid segment to represent the midfoot. This investigation used a rigid plastic foot plate described in Chapter 5, Section 5.4 that overlaid the midfoot region of the foot, which encompassed the navicular and cuboid. As described by Nester et al (2007) this technique aimed to provide a better definition of a rigid segment. Individual markers placed on the skin which are used by almost all skin mounted marker foot models are subject to considerable skin movement artefact, thus violating the assumption of defining it as rigid. As Nester et al (2006) and Lundgren et al (2007) reported that there is some motion between the navicular and cuboid, and it is not possible to accurately measure the individual movement of these bones from the skin surface. Therefore, it would support a method that defines them as one rigid segment. By attaching markers to a plastic plate it aimed to provide a more accurate representation of a rigid segment.

The results indicate that this technique provides a representation of the movement of the midfoot during the gait cycle that was perhaps an improvement comparabled to previous studies (Leardini et al 2007, MacWilliams et al 2003, DeMits et al 2012, and Simon et al 2006) that used skin mounted markers. For example, this investigation reports that the midfoot dorsiflexed relative to the calcaneus 5.7° (SD = 2.5°) on the left and 4.3° (SD = 3.8°) on the right during midstance. In contrast, DeMits et al (2012) and Leardini et al (2007) report less than 1° of dorsiflexion during this phase. While Nester et al (2006) and Lundgren et al (2007), using the gold standard intra-cortial pins, report that the navicular dorsiflexed 10° relative to the talus and the cuboid dorsiflexed 5° relative to the calcaneus during midstance.

However, there is less agreement between the results from this or others (DeMits et al 2012, MacWilliams et 2003 Leardini et al 2007, Jenkyn and Nicol 2007, Simon et al 2006) and the results from Nester et al (2006) and Lundgren et al (2007) in the range of frontal and transverse plane midfoot motion. This reflects the difficulty incurred due to the inability to measure talar motion using skin surface mounted markers. The measurement of the navicular relative to the talus was particularly distinct from the data provided through intra cortial bone pins. The movement of the bones within the midfoot are also described by some (Blackwood et al 2005, Pohl et al 2006, Hunt et al 2001a, and Wolf et al 2008) as dependent upon the movement of the calcaneus relative to the tibia or talus. This helps to demonstrate how the movement of joints within the foot are inter-dependent. Some (Wolf et al 2008, Pohl et al 2006, Eslami et al 2007, Dierks and Davis 2007) have described this as coupling. Wolf et al (2008) used a quasi-static method of moving the foot in a pronation and supination movement and measured the relationship between different bones within the foot. They reported that the movement of the calcaneus relative to the talus directly affects the articulation of the navicular relative to the talus ($r^2 = 0.97$) and the cuboid relative to the calcaneus ($r^2 = 0.83$) (Wolf et al 2008).

Pohl et al (2006), used a much simpler approach of dividing the foot into only forefoot and rearfoot rigid segments. Pohl et al (2006) described how there is a strong relationship between the range of frontal plane motion of the calcaneus relative to the tibia and the range of motion of the forefoot relative to the rearfoot in the sagittal plane ($r = -0.968$ ($p = 0.027$), and transverse plane ($r = 0.980$ ($p = 0.014$)). Although, in the frontal plane the correlation values were only $r = -0.319$ (p

= 0.762). In consideration of the large number of participants included in this present investigation, and the complex design of the foot model used, it would suggest that further investigations could investigate the coupling mechanisms between the joints of the foot. This should provide more information so to better understand how the joints of foot function inter-dependently.

In summary, the results from this section demonstrate the functional importance of the foot in aiding the movement of the body during gait. It has highlighted how the large range of sagittal plane motion between the different segments of the foot is important for the facilitation of movement forwards in the direction of travel. The inter-dependent function of the joints and functional complexes within the foot, allow it to provide support to body weight, stability and flexibility to accommodate for any terrain. However, the large inter-participant variation reported across all inter-segmental angles indicates the individuality in how the joints of the foot move during the gait cycle.

6.4 Results and Discussion – Research Question 1

The aim of this section is to demonstrate the results from this investigation, and present a discussion of these with the surrounding literature for each individual Root et al hypothesis, within Research Question 1. This will aim to determine if the Root et al (1977) description of the movement, and function of what they propose is the normal foot during the gait cycle, is in agreement with kinematic data collected from asymptomatic participants The graphs presented for each Inter-segmental angle in Section 6.3 should also be used within this section as a comparison to the Root et al (1977) description of the function, and movement of the foot during the gait cycle.

6.4.1 Root et al Hypothesis 1 - At initial heel contact the subtalar joint is supinated.

In the majority of feet the calcaneus is inverted (supinated) (left: 4.0° (SD = 3.9°) (77% of feet), right: 2.8° (SD = 3.3°) 79% of feet) relative to the tibia at initial heel contact (Table 6.7).

In most feet, the calcaneus was plantarflexed (left: -3.1° (SD = 4.2°) (80% of feet)), and abducted (left: 2.2° (SD= 3.7°), (72% of feet)) relative to the tibia at initial heel contact (Table 6.7). There is some inter-participant variation in the angle of the calcaneus relative to the tibia at initial heel contact (Figures 6.6a-6.6f). For example, on the right, in only 59% of feet was the calcaneus abducted relative to the tibia This may have contributed to the overall smaller mean value of 0.7° (SD=3.4°), compared to 2.2° (SD=3.7°) on the left.

Segment	Plane of Motion	Descriptive analysis (+ve DF, INV, ABD)	Angle at initial heel contact	
			Left (n= 99)	**Right** (n=100)
Calcaneus-Tibia	Sagittal (x)	Mean (°)	-3.1	-3.5
		SD (°)	*4.2*	*4.4*
		95% CI (°)	*-3.9- -2.2*	*-4.4- -2.6*
		No .of feet DF angle (n, %)	*n=26 (26%)*	*n=20 (20%)*
		Max DF angle (°)	*6.8*	*10.2*
		Min DF angle (°)	*0.1*	*0.02*
		No. of feet PF angle (n, %)	*n=73 (74%)*	*n=80 (80%)*
		Max PF angle (°)	*-15.5*	*-19.4*
		Min PF angle (°)	*-0.1*	*-0.4*
	Frontal (y)	Mean (°)	4.0	2.8
		SD (°)	*3.9*	*3.3*
		95% CI (°)	*3.2- 4.8*	*2.2- 3.5*
		No. of feet INV angle (n, %)	*n=85 (86%)*	*n=79 (79%)*
		Max INV angle (°)	*14.6*	*14.4*
		Min INV angle (°)	*0.01*	*0.2*
		No .of feet EVER angle (n,%)	*n=14 (14%)*	*n=21 (21%)*
		Max EVER angle (°)	*-7.9*	*-4.3*
		Min EVER angle (°)	*-0.6*	*-0.01*
	Transverse (z)	Mean (°)	2.2	0.7
		SD (°)	3.7	3.4
		95% CI (°)	1.5- 2.9	0.1- 1.1
		No. of feet ABD angle (n,%)	*n=71 (72%)*	*n=59 (59%)*
		Max ABD angle (°)	*13.6*	*10.2*
		Min ABD angle (°)	*0.4*	*0.1*
		No. of feet ADD angle (n, %)	*n=28 (28%)*	*n=41 (41%)*
		Max ADD angle (°)	*-9.2*	*-10.8*
		Min ADD angle (°)	*-0.01*	*-0.2*

Table 6.7 describes the mean sagittal, frontal and transverse plane angle of the calcaneus relative to the tibia at initial heel contact. The number of feet displaying a DF/PF, INV/EVER, ABD/ADD angle (n, %). The Max/Min DF/PF, INV/EVER, ABD/ADD angles (°).

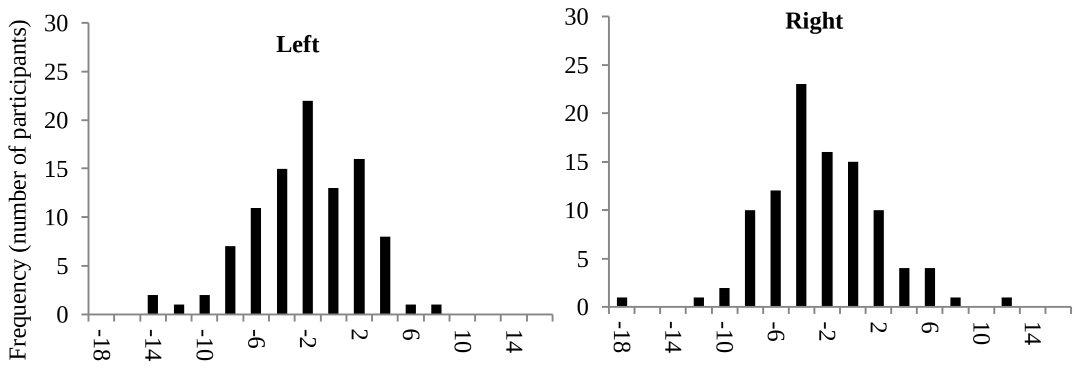


Figure 6.6a (left) and 6.6b (right): Histogram demonstrating the inter-participant variation in the sagittal plane angle of the calcaneus relative to the tibia at initial heel contact (degrees). Positive angle: Dorsiflexed, Negative angle: Plantarflexed

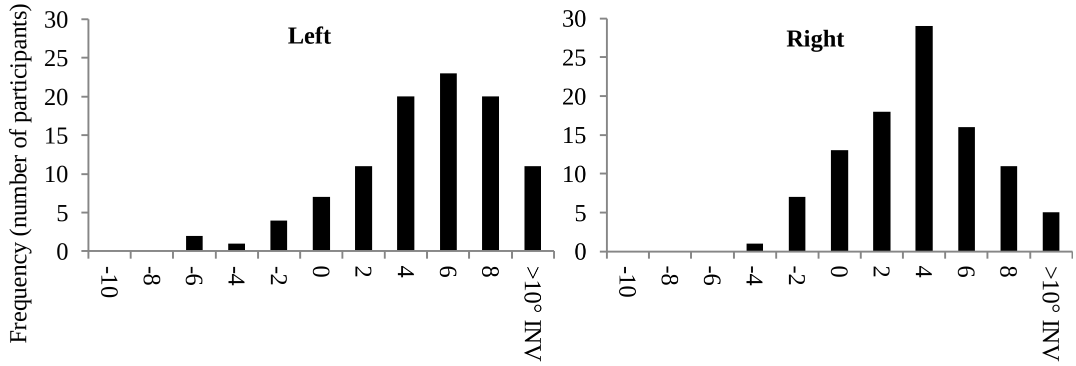


Figure 6.6c (left) and 6.6d (right): Histogram demonstrating the inter-participant variation in the frontal plane angle of the calcaneus relative to the tibia at initial heel contact (degrees). Positive angle: Inverted, Negative angle: Everted

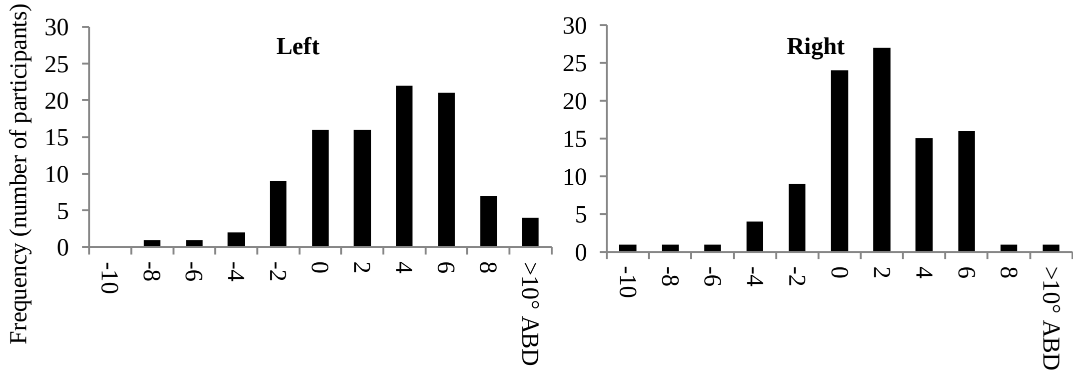


Figure 6.6e (left) and 6.6f (right): Histogram demonstrating the inter-participant variation in the transverse plane angle of the calcaneus relative to the tibia at initial heel contact (degrees). Positive angle: Abducted, Negative angle: Adducted

Discussion

The calcaneus was inverted relative to the tibia at initial heel contact. This suggests that in agreement with Root et al (1977) the subtalar joint is in a supinated position at this stage of the gait cycle. The results from this investigation are similar to others (Leardini et al 2007, Cornwall and McPoil 1999a, Kitaoka et al 2006, Lundgren et al 2007, Arndt et al 2004) who reported that the calcaneus was inverted relative to the tibia or talus between 2° to 2.5° at initial heel contact. All investigations and this have used RCSP as the zero reference position to determine the position of any inter-segmental angles calculated, therefore emphasising the similarity between them.

Supination at the subtalar joint is a tri-planar motion. In this Root et al (1977) hypothesis only the frontal plane component of the angle between the calcaneus relative to the tibia has been used to indicate supination through inversion, or pronation through eversion. A limitation of this and any other investigations is that it is not possible to measure talar motion when using skin mounted markers. However, Root et al (1977) proposed that when weight bearing, the calcaneus would move in the frontal plane, and the talus would move upon the calcaneus in the sagittal and transverse planes. Root et al (1977) advocated using the frontal plane movement of the calcaneus to infer the movement of the subtalar joint, as they also described how it was no possible to visualise talar motion from the skins surface. Therefore, it would suggest that using the frontal plane angle of the calcaneus is an appropriate representation of their description.

In the sagittal and transverse planes, the calcaneus was in most feet plantarflexed, and abducted relative to the tibia. This is consistent with the results of Kitaoka et al (2006), Cornwall and McPoil (1999a) and Leardini et al (2007) who similarly reported a plantarflexed angle of between 1° to 4°, and an abducted angle of up to 2°. Although Hunt et al (2001a) and Moseley et al (1996) both reported that the calcaneus was dorsiflexed relative to the tibia at initial contact. This could be related to the position of the foot used to define zero degrees of rotation (0°) in these investigations, as they did not use RCSP as this and other investigations have used.

However, there is some inter-participant variation in the direction of the angle in the frontal, sagittal and transverse planes reported by this investigation, and others (Leardini et al 2007, Cornwall and McPoil 1999a, Hunt et al 2001a, Kitaoka et al 2006, Lundgren et al 2007, Arndt et al 2004). For example, in the transverse plane, although the mean value in this investigation indicates an abducted angle, only 72% of feet on the left, and 59% of feet on the right were abducted. Lundgren et al (2007) reported similar inter-participant variation. From just the five feet tested the calcaneus was abducted relative to the tibia in three feet, and adducted in two feet at initial heel contact. This suggests that contrary to what Root et al (1977) described it is not possible to state a specific angle, or position of the foot that is proposed to represent the normal foot. Nor is it wise to assume that all feet will function the same.

Overall, the results from this investigation are in agreement with the Root et al (1977) description. This is because even though not in all feet was the calcaneus inverted relative to the tibia at initial heel contact, it does indicate a definite trend in the position of the subtalar joint at initial heel contact.

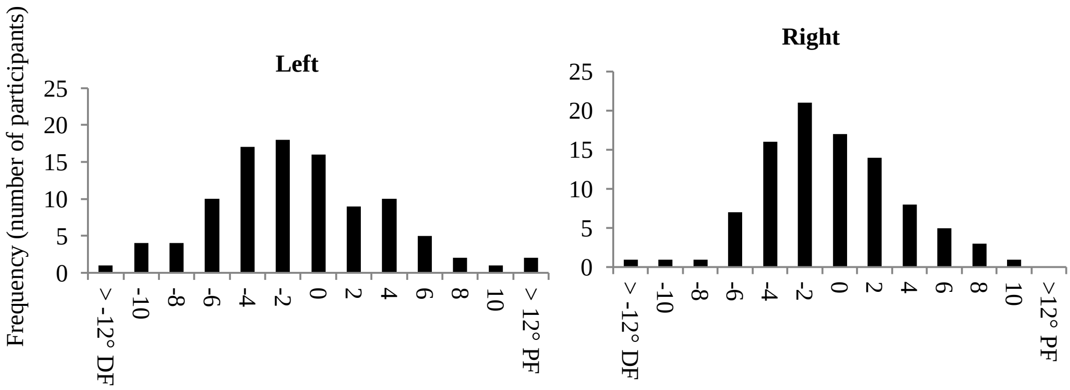
6.4.2 Root et al Hypothesis 2 - At initial heel contact the midtarsal joint is pronated (dorsiflexed and abducted) around the oblique axis, and supinated (inverted) around the longitudinal axis.

The mean values indicate that the midfoot was inverted (left: 0.5° (SD =2.9°)), but contrary to hypothesis it was plantarflexed (left: -2.1° (SD = 5.2°) and adducted (left: -0.7° (SD =2.6°)) relative to the calcaneus at initial heel contact (Table 6.8).

There is some inter-participant variation across all planes of motion (Figure6.7a-6.7f). For example on the left, the midfoot was plantarflexed in 71% of feet, inverted in 55% of feet and adducted in 67% of feet relative to the calcaneus. There is similar inter-participant variation on the right.

Segment	Plane of Motion	Descriptive analysis (+ve angle DF, INV,ABD)	Angle at initial heel contact	
			Left (n=99)	Right (n=95)
Midfoot-Calcaneus	Sagittal (x)	Mean (°)	-2.1	-1.6
		SD (°)	5.2	4.1
		95% CI (°)	-3.1- -1.1	-2.4- -0.8
		No. of feet DF angle (n, %)	n=29 (29%)	n=32 (32%)
		Max DF angle (°)	17.2	8.5
		Min DF angle (°)	0.1	0.4
		No. of feet PF angle (n, %)	n=70 (71%)	n=63 (66%)
		Max PF angle (°)	-18.5	-16.7
		Min PF angle (°)	-0.03	-0.2
	Frontal (y)	Mean (°)	0.5	2.2
		SD (°)	2.9	3.0
		95% CI (°)	-0.1- 1.1	1.6- 2.8
		No. of feet INV angle (n, %)	n=54 (55%)	n=78 (82%)
		Max INV angle (°)	7.7	9.8
		Min INV angle (°)	0.1	0.1
		No. of feet EVER angle (n, %)	n=45 (45%)	n=17 (18%)
		Max EVER angle (°)	-8.1	-9.3
		Min EVER angle (°)	-0.03	-0.02
	Transverse (z)	Mean (°)	-0.7	-0.2
		SD (°)	2.6	2.8
		95% CI (°)	-1.2- -0.4	-0.7- 0.4
		No .of feet ABD angle (n, %)	n=33 (33%)	n=49 (52%)
		Max ABD angle (°)	11.7	10.1
		Min ABD angle (°)	0.01	0.2
		No .of feet ADD angle (n, %)	n=66 (67%)	n=46 (48%)
		Max ADD angle (°)	-6.8	-7.8
		Min ADD angle (°)	-0.1	-0.6

Table 6.8 describes the mean sagittal, frontal and transverse plane angle of the midfoot relative to the calcaneus at initial heel contact. The number of feet displaying a DF/PF, INV/EVER, ABD/ADD angle (n, %). The Max/Min DF/PF, INV/EVER, ABD/ADD angles (°).



Figures 6.7a (left) and 6.7b (right):Histogram demonstrating the inter-participant variation in the sagittal plane angle of the midfoot relative to the calcaneus at initial heel contact. Positive angle: Dorsiflexed, Negative angle: Plantarflexed

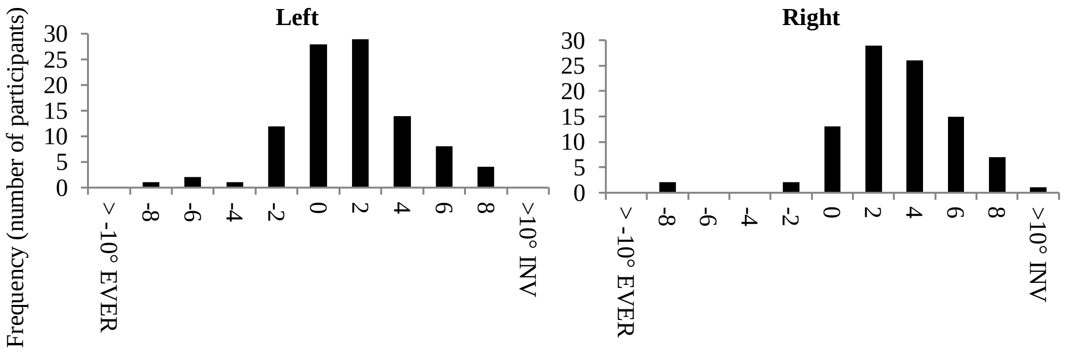


Figure 6.7c (left) and 6.7d (right): Histogram demonstrating the inter-participant variation in the frontal plane angle of the midfoot relative to the calcaneus at initial heel contact. Positive angle: Inverted, Negative angle: Everted

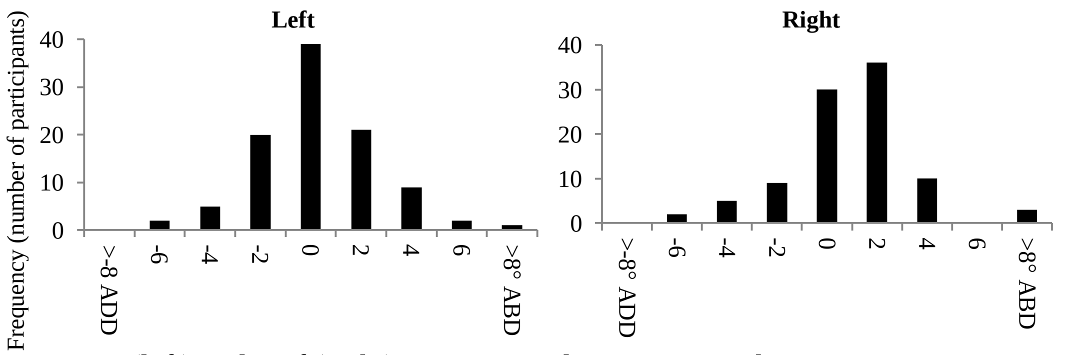


Figure 6.7e (left) and 6.7f (right): Histogram demonstrating the inter-participant variation in the transverse plane angle of the midfoot relative to the calcaneus at initial heel contact. Positive angle: Abducted, Negative angle: Adducted

Discussion

In this investigation the midfoot was inverted relative to the calcaneus at initial heel contact. This is in agreement with Root et al (1977), and the results from other

(Leardini et al 2007, DeMits et al 2012 Rattanaprasert et al 1999, Kitaoka et al 2006, Hunt et al 2001a and Jenkyn and Nicol 2007) investigations that have either measured the midfoot as an individual rigid segment (Leardini et al 2007, DeMits et al 2012, Jenkyn and Nicol 2007), or the forefoot relative to the rearfoot (Rattanaprasert et al 1999, Kitaoka et al 2006, Hunt et al 2001a). They reported that the midfoot was inverted between 1°-3° relative to the calcaneus at initial heel contact.

Root et al (1977) proposed that the pronated position of the midtarsal joint around its oblique axis at initial heel contact, and its continued pronation during the contact phase is an integral component of normal foot function. If the midtarsal joint was plantarflexed, and adducted at initial heel contact, it was proposed by them to be a cause of severe soft tissue deformity. However, this investigation and other investigations (Leardini et al 2007, DeMits et al 2012, Jenkyn and Nicol 2007, Kitaoka et al 2006, Rattanaprasert et al 1999, Hunt et al 2001a) report that the midfoot was plantarflexed, and adducted relative to the calcaneus at initial heel contact, and not dorsiflexed or abducted. All feet included in this, and those other (investigations are asymptomatic.

The measurement of the midfoot as one rigid segment which combines the navicular and cuboid together can have several limitations. Most notably this would be that it is not possible to measure the individual movements or angles of the navicular and cuboid. For example, Lundgren et al (2007) reported that at initial heel contact, the navicular was dorsiflexed relative to the talus, but the cuboid was plantarflexed relative to the calcaneus. These contrasting movements, or angles of the bones within the midfoot help to emphasise that contrary to Root et al (1977), there cannot be two axes of rotation at the midtarsal joint, or midfoot. This is because sagittal plane motion is proposed to only occur around the oblique axis. Therefore, it is not possible for there to be contrasting angles at the midtarsal joint at the same time around the same axis.

The large inter-participant variation in the angle of the midfoot and direction of motion suggests that in asymptomatic individuals, there is not a definitive position of the midfoot at initial heel contact. For example, in the transverse plane, this investigation reports that in only 66% of feet on the left, and 48% of feet on the right, was the midfoot adducted relative to the calcaneus at initial heel contact. This amount of variation is in agreement with those measuring the midfoot as a rigid segment, or the individual bones of the midfoot. Lundgren et al (2007) described how the navicular relative to talus and cuboid relative to the calcaneus was abducted in some feet, and adducted in others at initial heel contact. There was also inter-trial variation by some feet who demonstrated both positions over different walking trials. There is similar large inter-participant variation in sagittal and frontal planes. Overall, this suggests that there is highly varied function within the midfoot, much more so than between the calcaneus relative to the tibia at initial heel contact (Hypothesis 1).

Overall, the results from this investigation are not in agreement with Root et al (1977). . This is because the midfoot was plantarflexed, inverted, and adducted relative to the calcaneus at initial heel contact, and not dorsiflexed or abducted as Root et al (1977) described. However there is considerable inter-participant variation in the position of the midfoot. This suggests it is not possible to describe specific positions of this region of the foot to represent the asymptomatic foot.

6.4.3 Root et al Hypothesis 3 – The calcaneus will evert from neutral 4-6° during the contact phase.

In most feet, the calcaneus was everted less than 4°-6° relative to the tibia at forefoot loading (left: 1.9° (SD=3.6°)). During the contact phase, the calcaneus was not in an everted angle greater than 4°-6° relative to the tibia (left: 1.9° (SD=3.7°)), nor did it evert during this phase more than 4°-6° (left: -2.2° (SD=1.8°)) (Table 6.9).

The calcaneus everted more than 4° relative to the tibia at forefoot loading in 6/90 feet on the left, and 4/91 feet on the right (Figure 6.8a and 6.8b). The range of calcaneal eversion during the contact phase was greater than 4° in 13/90 feet on the left, and 10/91 feet on the right (Figure 6.8e and 6.8f).The calcaneus was inverted 9.2° (SD = 5.0°) on the left, and 9.0° (SD = 5.1°) on the right relative to the tibia when placed in NCSP.

Segment	Plane of motion	Descriptive analysis (+ve angle/ ROM INV)	Gait Parameter						Angle at NCSP*	
			ROM during contact phase		Peak angle of EVER during contact phase		Angle at forefoot loading			
			Left	Left	Left	Right	Left	Right	Left	Right
Calcaneus-Tibia (Left n=91, Right n=90) **	Frontal (y)	Mean (°)	-2.2	-1.7	1.9	0.9	1.9	1.4	9.2	9.0
		SD (°)	*1.8*	*2.1*	*3.7*	*2.9*	*3.6*	*2.9*	*5.0*	*5.1*
		95% CI (°)	*-2.6- -1.8*	*-2.1- 1.2*	*1.2- 2.8*	*0.3- 1.5*	*1.5- 2.9*	*0.7- 1.9*	*8.2- 2.9*	*7.9- 10.1*
		No. of feet INV angle/ ROM (n, %)	*n=7 (8%)*	*n=17 (19%)*	*n=69 (77%)*	*n=54 (77%)*	*n=70 (78%)*	*n=61 (67%)*	*n=87 (97%)*	*n=88 (97%)*
		Max INV angle/ROM (°)	*4.9*	*6.9*	*13.3*	*9.6*	*13.4*	*9.6*	*19.5*	*29.1*
		Min INV angle/ROM (°)	*0.7*	*0.9*	*0.2*	*0.1*	*0.2*	*0.03*	*0.3*	*0.6*
		No. of feet EVER angle/ ROM (n, %)	*n=83 (92%)*	*n=74 (81%)*	*n=21 (23%)*	*n=37 (41%)*	*n=20 (22%)*	*n=30 (33%)*	*n=3 (3%)*	*n=3 (3%)*
		Max EVER angle/ROM(°)	*-6.6*	*-5.9*	*-8.8*	*-5.4*	*-8.6*	*-5.1*	*-0.9*	*-2.9*
		Min EVER angle/ROM (°)	*-0.6*	*-0.6*	*-0.1*	*-0.01*	*-0.1*	*-0.03*	*-0.4*	*-0.1*

Table 6.9 describes the mean frontal plane angle and range of motion of the calcaneus relative to the tibia during the contact phase and in NCSP. The number of feet displaying an INV/EVER angle or range of motion (n, %). The Maximum/Minimum INV/EVER angle or range of motion (°). * Measured relative to RCSP which is 0°. ** n= 8 (left) and n=10 (right) no data for calc-tibia in NCSP (Data set B), therefore data omitted from gait parameters for this hypothesis.

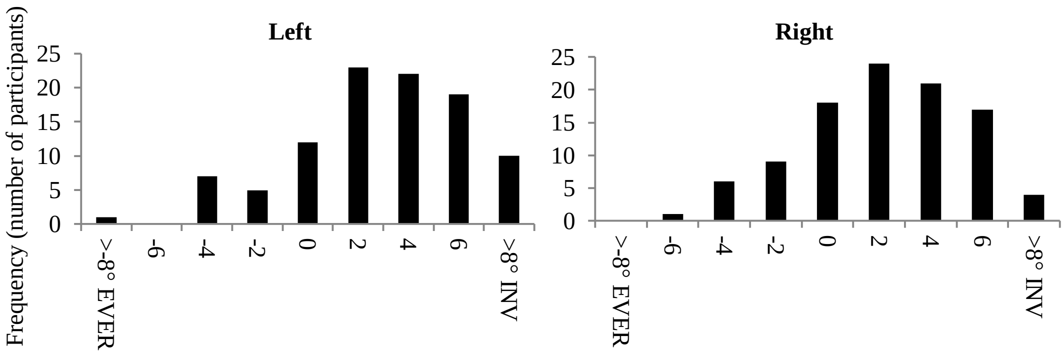


Figure 6.8a (left) and 6.8b (right): Histogram demonstrating the inter-participant variation in the frontal plane angle of the calcaneus relative to the tibia at forefoot loading. Positive angle: Inverted, Negative angle: Everted

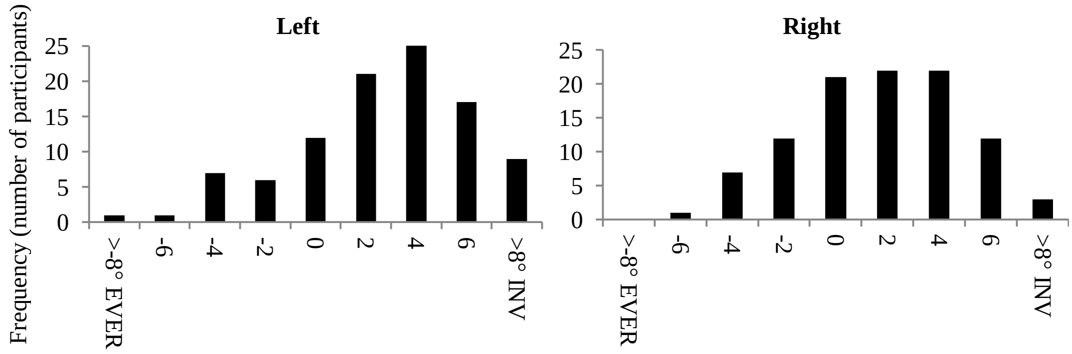


Figure 6.8c (left) and 6.8d (right): Histogram demonstrating the inter-participant variation in the peak angle of eversion of the calcaneus relative to the tibia during the contact phase. Positive angle: Inverted, Negative angle: Everted

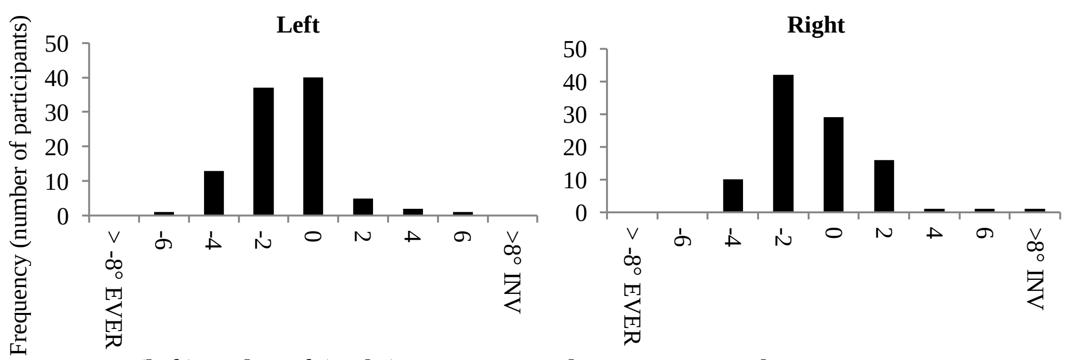


Figure 6.8e (left) and 6.8f (right): Histogram demonstrating the inter-participant variation in the range of frontal plane motion of the calcaneus relative to the tibia during the contact phase. Positive range of motion: Inversion, Negative range of motion: Eversion

Discussion

The results from this investigation, and others (Kitaoka et al 2006, Cornwall and McPoil 1999a, Leardini et al 2007, Hunt et al 2001a, Jenkyn and Nicol 2007, Rattanaprasert et al 1999, Moseley et al 1996, Simon et al 2006) demonstrate that in agreement with Root et al (1977), in most feet the calcaneus will evert (pronate) relative to the tibia during the contact phase. However, in most feet the range of frontal plane motion of the calcaneus relative to the tibia during the contact phase is less than 4°- 6° eversion, and the calcaneus is not everted between 4°- 6° at forefoot loading. This is in agreement with others (Kitaoka et al 2006, Cornwall and McPoil 1999a, Leardini et al 2007, Jenkyn and Nicol 2007, Rattanaprasert et al 1999, Simon et al 2006), who reported between -2° and -3° eversion during this phase, a similar range of motion to the results from this investigation. This suggests that Root et al (1977) has considerably over-estimated the range of frontal plane motion at the subtalar joint during the contact phase.

The Root et al hypothesis states that in the normal foot there will be 4°-6° of eversion from the neutral position of the subtalar joint during this phase. This is in reference to the anatomical alignment of the subtalar joint, where it is neither pronated nor supinated. The angle of the foot in this position can be measured using NCSP. However, this and other (Kitaoka et al 2006, Cornwall and McPoil 1999a, Leardini et al 2007, Jenkyn and Nicol 2007, Rattanaprasert et al 1999, Simon et al 2006) investigations have used the position of all inter-segmental angles in RCSP to define zero degrees of rotation. Therefore the position or movement of the calcaneus relative to the tibia during the gait cycle is measured relative to this, which is not the neutral position of the subtalar joint. This may explain the large difference in the results, when compared to what Root et al (1977) described.

In this investigation, to measure the frontal plane angle of the calcaneus relative to the tibia in NCSP, it is measured from RCSP. Therefore the angle in NCSP will be in an inverted or everted angle as the foot has been manipulated into a different position than the zero reference position. However, Root et al (1977) hypothesised that in the normal foot, the subtalar joint should be in a neutral position in RCSP, or within 2° everted to 2° inverted, but the mean results for NCSP indicate a much greater inverted angle. As the mean angle for NCSP is more inverted than the angle at initial heel contact, it is not possible to measure the movement of it from the neutral position of the subtalar joint. This is because it would have to invert after initial heel contact, and this pattern of movement was not demonstrated by any foot from the cohort.

It would appear to be a limitation of this investigation that it was not possible to test exactly what Root et al (1977) described as none of the feet tested met the kinematic characteristics of the normal foot described by Root et al (1977). However, this investigation and others (McPoil and Cornwall 1994, McPoil and Cornwall 1996a) have reported that the subtalar joint is not in a neutral position in almost all of the feet when measured in NCSP. In consideration of the number of participants used in this and those other investigations, it strongly suggests that the neutral position of the subtalar joint is not a position used during gait, or achieved in RCSP. It also indicates that what has been tested in this Root et al hypothesis is the most logical, and closest representation to what Root et al (1977) described.

The mean results from this investigation and others (Leardini et al 2007, Cornwall and McPoil 1999a, Kitaoka et al 2006) demonstrate that the calcaneus is inverted, and not everted relative to the tibia at forefoot loading. This indicates that contrary to Root et al (1977), the subtalar joint is not in a peak angle of eversion or pronation at forefoot loading, and nor does it need to be for the foot to achieve plantigrade contact with the supporting surface. Some investigations (Hunt et al 2001a, Jenkyn and Nicol 2007, Moseley et al 1996, Rattanaprasert et al 1999) reported that the calcaneus is in an everted position relative to the tibia at forefoot loading. Although they have all also reported that the calcaneus was in an everted position at initial heel contact. Hunt et al (2001a) and Moseley et al (1996) have not used RCSP as the zero reference position, and have instead placed the calcaneus in an inverted position which may also explain the greater everted angle, and range of frontal plane motion of the calcaneus relative to the tibia.

Overall the results from this investigation are not in agreement with the Root et al (1977) description. . This is because contrary to Root et al (1977) the frontal plane angle of the calcaneus relative to the tibia is not everted 4°-6° at forefoot loading, and nor does it evert 4-6° during the contact phase.

6.4.4 Root et al Hypothesis 4 - The subtalar joint will stop pronating when forefoot contact is made and will supinate during midstance.

The calcaneus everted (pronated) relative to the tibia during midstance in most feet (83% on the left and 82% on the right) (Table 6.10) (Figures 6.9c-6.9d).

Table 6.10 demonstrates that in all feet the calcaneus dorsiflexed (right: 15.4° (SD = 3.5°)) and in most feet everted (right: -4.3° (SD = 4.4°) n=82 (83%)), and adducted (right: -2.7° (SD= 5.5°), n= 72 (72%)) relative to the tibia during midstance. In the transverse plane, the calcaneus adducted relative to the tibia during midstance in only 61% of feet on the left and 72% of feet on the right indicating some inter-subject variation.

Segment	Plane of motion	Descriptive analysis (+ve DF, INV, ABD)	ROM during midstance phase Left	Right
Calc-Tibia Left n=99 Right n=100	Sagittal (x)	Mean (°)	14.8	15.4
		SD (°)	*3.2*	*3.5*
		95% CI (°)	*14.2- 15.5*	*14.7- 16.1*
		No .of feet DF ROM (n, %)	*n=99 (100%)*	*n=100 (100%)*
		Max DF ROM(°)	*25.6*	*24.2*
		Min DF ROM (°)	*8.1*	*6.2*
		No. of feet PF ROM (n, %)	*0*	*0*
		Max PF ROM (°)	-	-
		Min PF ROM (°)	-	-
	Frontal (y)	Mean (°)	-4.5	-4.3
		SD (°)	*5.3*	*4.4*
		95% CI (°)	*-5.5- -3.4*	*-5.2- -3.4*
		No .of feet INV ROM (n, %)	*n=17 (17%)*	*n=18 (18%)*
		Max INV ROM (°)	*10.6*	*6.1*
		Min INV ROM (°)	*2.9*	*1.8*
		No .of feet EVER ROM (n , %)	*n=82 (83%)*	*n=82 (82%)*
		Max EVER ROM (°)	*-16.5*	*-12.8*
		Min EVER ROM (°)	*-2.2*	*-0.6*
	Transverse (z)	Mean (°)	-1.9	-2.7
		SD (°)	*6.1*	*5.5*
		95% CI (°)	*-3.2- -0.8*	*-3.8- -1.6*
		No .of feet ABD ROM (n, %)	*n=39 (39%)*	*n=28 (28%)*
		Max ABD ROM (°)	*8.7*	*9.7*
		Min ABD ROM (°)	*2.3*	*0.1*
		No. of feet ADD ROM (n, %)	*n=60 (61%)*	*n=72 (72%)*
		Max ADD ROM (°)	*-12.1*	*-11.2*
		Min ADD ROM (°)	*-2.8*	*-2.5*

Table 6.10 describes the mean range of sagittal, frontal and transverse plane motion of the calcaneus relative to the tibia during midstance. The number of feet displaying DF/PF, INV/EVER, ABD/ADD (n, %). The Max/Min range of DF/PF, INV/EVER, ABD/ADD (°).

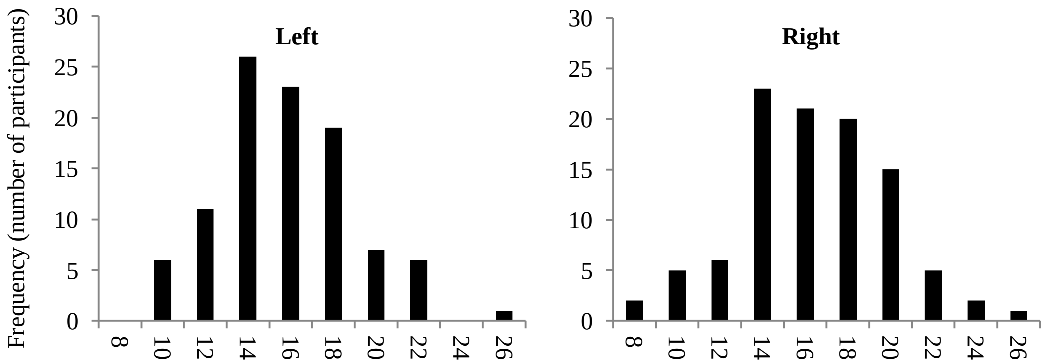


Figure 6.9a (left) and 6.9b (right): Histogram demonstrating the inter-participant variation in the range of sagittal plane motion of the calcaneus relative to the tibia during midstance. Positive range of motion: Dorsiflexion, Negative range of motion: Plantarflexion

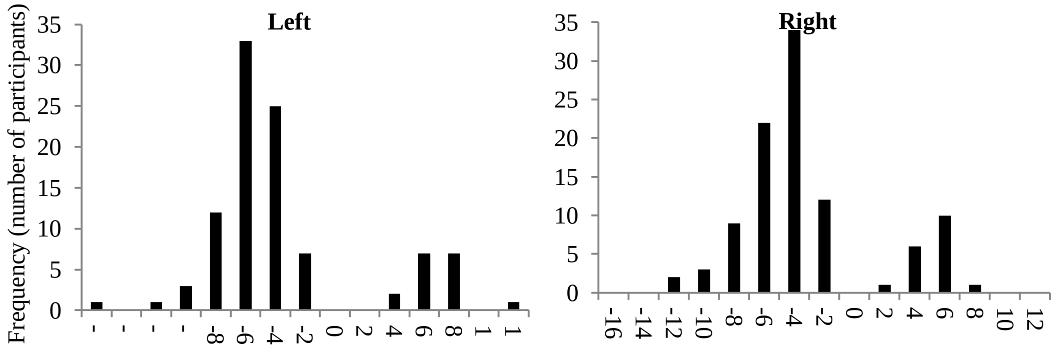


Figure 6.8c (left) and 6.8d (right): Histogram demonstrating the inter-participant variation in the range of frontal plane motion of the calcaneus relative to the tibia during midstance. Positive range of motion: Inversion, Negative range of motion: Eversion

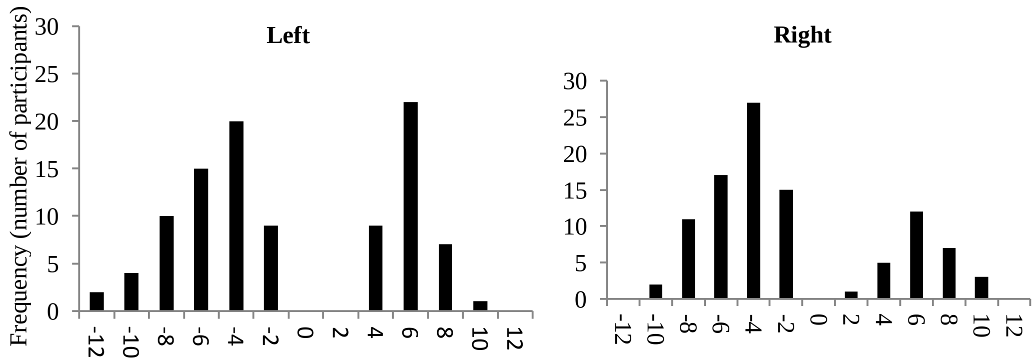


Figure 6.8e (left) and 6.8f (right): Histogram demonstrating the inter-participant variation in the range of transverse plane motion of the calcaneus relative to the tibia during midstance. Positive range of motion: Abduction, Negative range of motion: Adduction

Discussion

Pronation of the subtalar joint during midstance was described by Root et al (1977) and others (Michaud 1997, Valmassey 1995, Lorimer et al 2002)to be an abnormal movement of the foot. It was proposed to be a cause of injury and deformity to the soft and bony tissues of the foot, leg and lower limb. However, the results from this investigation and many others (Kitaoka et al 2006, Leardini et al 2007, Cornwall and McPoil 1999, Hunt et al 2001, Jenkyn and Nicol 2007, Simon et al 2006, Moseley et al 1996) demonstrate that in asymptomatic feet the calcaneus will evert relative to the tibia or talus during midstance (Lundgren et al 2007). Thus, inferring that the subtalar joint is in a pronated position and pronating during midstance. As all participants included in this and other (Kitaoka et al 2006, Leardini et al 2007, Cornwall and McPoil 1999, Hunt et al 2001, Jenkyn and Nicol 2007, Lundgren et al 2007, Simon et al 2006, Moseley et al 1996) investigations are asymptomatic. It indicates that pronation of the subtalar joint during midstance is neither abnormal, or a direct cause of symptoms.

This investigation reports -4.5° (SD = 5.3°) on the left, and -4.3° (SD = 4.4°) on the right eversion of the calcaneus relative to the tibia during midstance. This is similar to others (Kitaoka et al 2006, Leardini et al 2007, Cornwall and McPoil 1999a, Hunt et al 2001a, Moseley et al 1996) who have reported between -2° to -5° eversion of the calcaneus relative to the tibia. Lundgren et al (2007) reported a mean of approximately -5° eversion of the calcaneus relative to the talus during midstance. However, as indicated by the graphs in Lundgren et al (2007) there is large inter-participant variation in the movement of the calcaneus relative to the tibia. There is also a difference in the range of frontal plane motion of the calcaneus relative to the tibia or talus between different walking trials by the same person. This is also indicated by the results from this investigation. The maximum and minimum values suggest that some feet everted (or inverted) considerably more or less than the mean value. Therefore, contrary to Root et al (1977) there is no specific movement pattern of the calcaneus relative to the tibia talus or tibia during midstance in asymptomatic feet. The results of this investigation and others (Kitaoka et al 2006, Leardini et al 2007, Cornwall and McPoil 1999a, Hunt et al 2001a, Jenkyn and Nicol 2007, Lundgren et al 2007, Simon et al 2006, Moseley et al 1996), indicate that contrary to Root et al (1977), the maximum everted position of the subtalar joint during the stance phase of walking is not at forefoot loading. Instead, the peak angle of eversion occurred during midstance. The calcaneus was 5.9° (SEM = 0.5), ($p = <0.001$) on the left and 5.0° (SEM = 0.5), (p = <0.001) on the right more everted relative to the tibia during midstance than at forefoot loading.

Root et al (1977) infer that as soon as the forefoot has made flat plantigrade contact, there will be a rapid change in the direction of movement to inversion. However, as demonstrated by the graph in Section 6.3 and as reported by many (Kitaoka et al 2006, Leardini et al 2007, Cornwall and McPoil 1999a, Hunt et al 2001a, Jenkyn and Nicol 2007, Simon et al 2006) the frontal plane movement of the calcaneus relative to the tibia during midstance does not demonstrate any rapid or abrupt changes in direction. The movement is much more smooth. McPoil and Hunt (1995) and Nigg (2001) proposed that the speed of movement is a major contributory factor in the cause of injury or deformity to the soft and bony tissues of the foot and leg. Possibly more so than the range or direction of motion.

Pronation and supination of the subtalar joint are tri-planar motions. However, it is only the frontal plane component of this movement that has been used to indicate pronation through eversion of the calcaneus relative to the tibia in this Root et al hypothesis. A limitation of this, and any other investigations using skin mounted markers is that it is unable to measure talar motion. However, Root et al (1977) proposed that when weight bearing the calcaneus would move in the frontal plane, and the talus would move in the sagittal and transverse planes upon the calcaneus. Therefore, it would suggest that using the frontal plane angle of the calcaneus seemed an appropriate representation of their description.

Root et al (1977) described how pronation of the subtalar joint consists of calcaneal eversion, with plantarflexion and adduction of the the talus upon the calcaneus. However, this investigation and others (Cornwall and McPoil 1999a, Hunt et al

2001a, Moseley et al 1996, Leardini et al 2007, Kitaoka et al 2006), report that the calcaneus dorsiflexed and adducted or abducted relative to the tibia during this phase.

In the sagittal plane the range of dorsiflexion reported by this, and other (Kitaoka et al 2006, Leardini et al 2007, Cornwall and McPoil 1999a, Hunt et al 2001a, Jenkyn and Nicol 2007, Simon et al 2006, Moseley et al 1996) investigations that have measured the calcaneus relative to the tibia is much greater than Arndt et al (2004) and Lundgren et al (2007) who have measured the calcaneus relative to the talus. This indicates that the ankle joint is the primary contributor to sagittal plane motion occurring between the calcaneus relative to the tibia during midstance. In the transverse plane, there is large inter-participant variation and a difference between investigations in the direction of transverse plane motion. This investigation and others (Cornwall and McPoil 1999, Hunt et al 2001, Moseley et al 1996) report that the calcaneus adducted relative to the tibia during midstance. While others (Leardini et al 2007, Kitaoka et al 2006) report that the calcaneus abducted relative to the tibia during this phase. However, in this investigation the calcaneus adducted relative to the tibia in only 61% of feet on the left and 72% of feet on the right. This indicates that there is some inter-participant variation in the direction of transverse plane motion, which may also explain the differences between investigations.

Overall, the results from this investigation are not in agreement with the Root et al (1977) description. This is because contrary to what Root et al (1977) proposed the calcaneus did not invert from forefoot loading. In the majority of feet the calcaneus continued to evert relative to the tibia to reach a peak angle of eversion during midstance. This also indicates that pronation of the subtalar joint should not be classified as an abnormal movement or as a cause of injury as all feet used in this and other investigations are asymptomatic.

6.4.5 Root et al Hypothesis 5 - The midtarsal joint will pronate (dorsiflex, evert and abduct) during midstance, and it will reach a position of maximum pronation at heel lift.

The mean results demonstrate that in most feet the midfoot everted (right: -2.8° (SD=3.2°) 89% of feet), dorsiflexed (right: 4.3° (SD=3.8°) 89%), and abducted (right: 1.8° (SD=1.4°) 85%) relative to the calcaneus during midstance.

At heel lift, the mean results indicate that the midfoot is in a dorsiflexed (right: 2.6° (SD = 3.7°)), everted (right: -0.9° (SD=2.8°)) and abducted (right 0.9° (SD=2.6°)) angle relative to the calcaneus. There is large inter-participant variation across all planes of motion for both gait parameters (Figures 6.10a-6.10f, 6.11a-6,11f). For example, the midfoot was everted relative to the calcaneus at heel lift in 59% of feet on the left, and 54% of feet on the right. Both 95% confidence intervals for this gait parameter are inclusive of everted, and inverted angles (right: 95% confidence interval = -1.0°- 0.2°, left: 95% confidence interval = -1.0°- 0.1°).

The midfoot was not in a maximally everted position relative to the calcaneus at heel lift. The peak angle of midfoot eversion relative to the calcaneus during midstance was -0.9° (SEM = 0.4), (p=0.007) on the left, and -0.8° (SEM = 0.4), (p=0.02) on the right greater than at heel lift.

Segment	Plane of Motion	Descriptive analysis (+ve angle/ ROM DF, INV, ABD)	ROM during midstance		Angle at heel lift	
			Left	Right	Left	Right
Midfoot-Calcaneus (Left n=99, Right n=95)	Sagittal (x)	Mean (°)	5.7	4.3	1.6	2.6
		SD (°)	*2.5*	*3.8*	*4.6*	*3.7*
		95% CI (°)	*5.2- 6.1*	*3.6- 5.1*	*0.6- 2.5*	*1.9- 3.4*
		No. of feet DF angle/ ROM (n, %) *Max DF angle/ ROM (°)* *Min DF angle/ ROM (°)*	*n=99 (100%)* *16.9* *1.5*	*n=85 (89%)* *11.5* *1.2*	*n=66 (67%)* *20.9* *0.1*	*n=76 (80%)* *12.9* *0.02*
		No. of feet PF angle/ ROM (n, %) *Max PF angle/ ROM (°)* *Min PF angle/ ROM (°)*	*n=0* *-* *-*	*n=10 (10%)* *-7.0* *-2.6*	*n=33 (33%)* *-8.6* *-0.02*	*n=19 (20%)* *-5.3* *-0.1*
	Frontal (y)	Mean (°)	-2.6	-2.8	-0.5	-0.9
		SD (°)	*2.5*	3.2	*2.7*	2.8
		95% CI (°)	*-3.1- -2.1*	-3.5- -2.2	*-1.0- 0.1*	-1.0- 0.2
		No. of feet INV angle/ ROM (n, %) *Max INV angle/ ROM (°)* *Min INV angle/ ROM (°)*	*n=11 (11%)* *7.7* *1.2*	*n=17 (18%)* *5.9* *1.7*	*n=43 (43%)* *7.4* *0.1*	*n=44 (46%)* *6.1* *0.4*
		No .of feet EVER angle/ ROM (n, %) *Max EVER angle/ ROM (°)* *Min EVER angle/ ROM (°)*	*n=88 (89%)* *-9.2* *-1.1*	*n=78 (89%)* *-9.2* *-1.1*	*n=58 (59%)* *-10.2* *-0.1*	*n=51 (54%)* *-12.7* *-0.02*
	Transverse (z)	Mean (°)	0.5	1.8	0.6	0.9
		SD (°)	*2.4*	*2.4*	*2.6*	*2.6*
		95% CI (°)	*0.02- 0.9*	*1.4- 2.2*	*0.1- 1.1*	*0.4- 1.5*
		No. of feet ABD angle/ ROM (n,%) *Max ABD angle/ ROM (°)* *Min ABD angle/ ROM (°)*	*n=59 (60%)* *5.5* *0.9*	*n=81 (85%)* *9.3* *1.1*	*n=65 (66%)* *11.4* *0.1*	*n=62 (65%)* *12.4* *0.1*
		No .of feet ADD angle/ ROM (n, %) *Max ADD angle/ ROM (°)* *Min ADD angle/ ROM (°)*	*n=40 (40%)* *-5.9* *-1.1*	*n=14 (15%)* *-5.6* *-0.8*	*n=36 (36%)* *-5.6* *-0.1*	*n=33 (35%)* *-4.1* *-0.01*

Table 6.11 describes the mean range of sagittal, frontal and transverse plane motion and angle of the midfoot relative to the calcaneus during midstance and at heel lift. The number of feet displaying range or angle of DF/PF, INV/EVER, ABD/ADD (n, %). The Max/Min range or angle of DF/PF, INV/EVER, ABD/ADD (°).

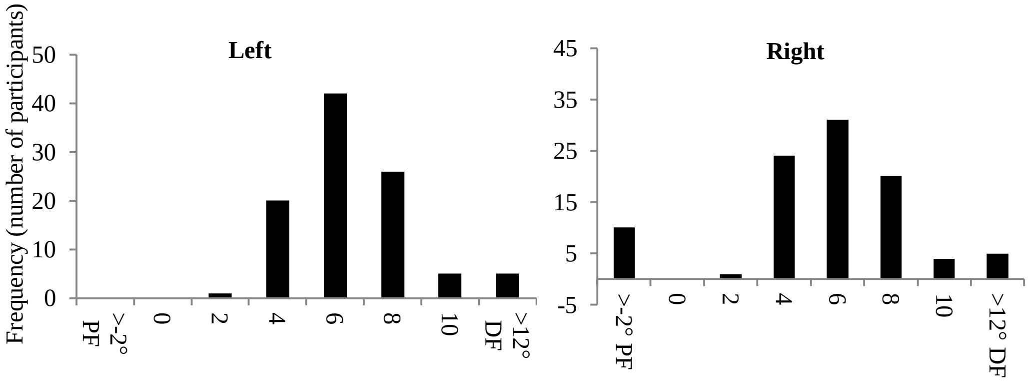


Figure 6.10a (left) and 6.10b (right): Histogram demonstrating the inter-participant variation in the range of sagittal plane motion of the midfoot relative to the calcaneus during midstance. Positive range of motion: Dorsiflexion, Negative range of motion: Plantarflexion

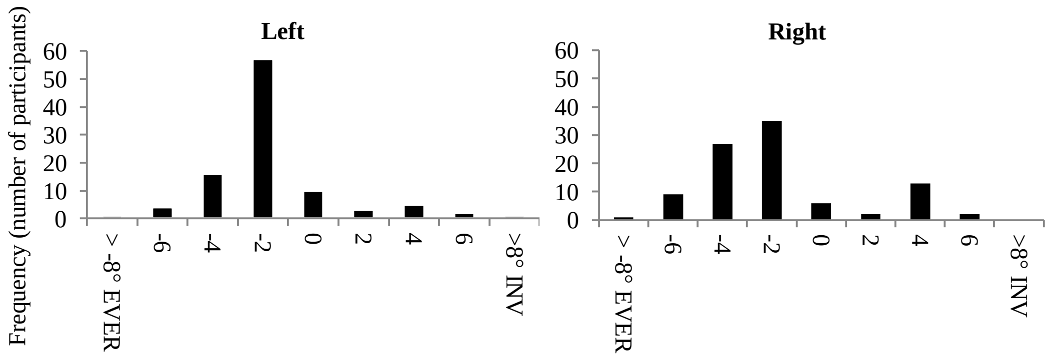


Figure 6.10c (left) and 6.10d (right): Histogram demonstrating the inter-participant variation in the range of frontal plane motion of the midfoot relative to the calcaneus during midstance. Positive range of motion: Inversion, Negative range of motion: Eversion

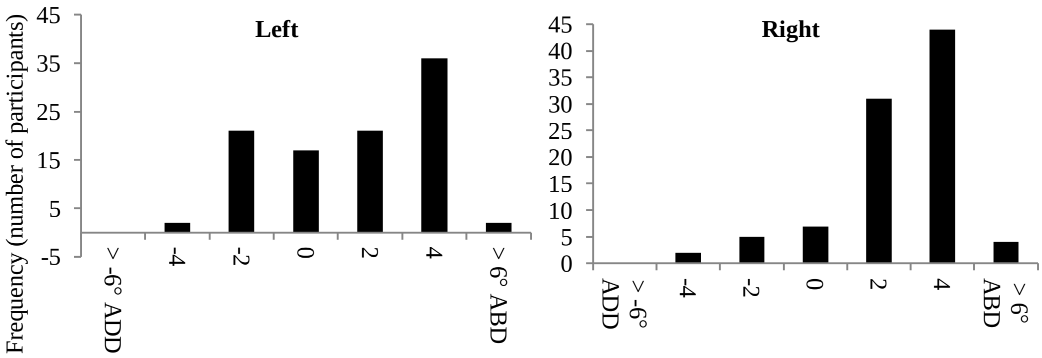


Figure 6.10e (left) and 6.10f (right): Histogram demonstrating the inter-participant variation in the range of transverse plane motion of the midfoot relative to the calcaneus during midstance. Positive range of motion: Abduction, Negative range of motion: Adduction

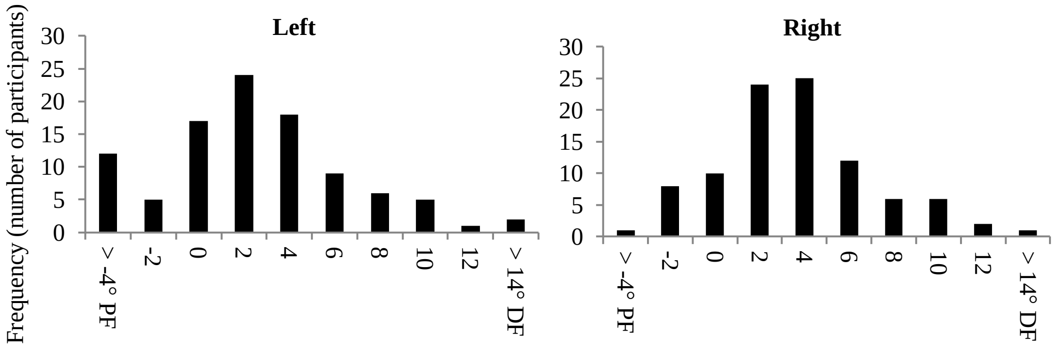


Figure 6.11a (left) and 6.11b (right): Histogram demonstrating the inter-participant variation in the sagittal plane angle of the midfoot relative to the calcaneus at heel lift. Positive angle: Dorsiflexed, Negative angle: Plantarflexed

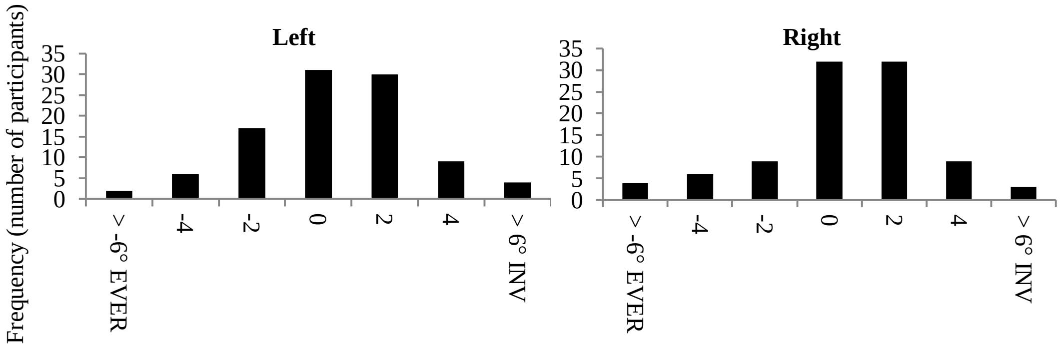


Figure 6.11c (left) and 6.11d (right): Histogram demonstrating the inter-participant variation in the frontal plane angle of the calcaneus relative to the tibia at heel lift. Positive angle: Inverted, Negative angle: Everted

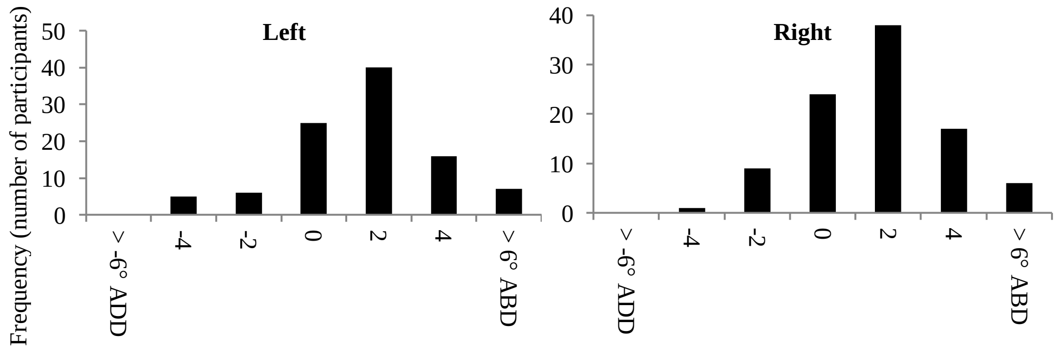


Figure 6.11e (left) and 6.11f (right): Histogram demonstrating the inter-participant variation in the transverse plane angle of the calcaneus relative to the tibia at heel lift. Positive angle: Abducted, Negative angle: Adducted

Discussion

In agreement with Root et al (1977), the results from this investigation and others (DeMits et al 2012, Leardini et al 2007, Lundgren et al 2007, Nester et al 2006, Jenkyn and Nicol 2007) demonstrate that the midfoot (or navicular and cuboid) dorsiflexed, everted, and abducted relative to the calcaneus (or talus) during midstance. This indicates that midfoot pronated during midstance.

Root et al (1977) proposed that supination of the subtalar joint would aid pronation of the midtarsal joint, around both of its axes. However, this investigation and those previously discussed have reported that the calcaneus everted relative to the tibia or talus during midstance. This indicates that the subtalar joint pronated during midstance, and contrary to Root et al (1977) the midfoot also pronated relative to the calcaneus in most feet during midstance. Pronation of the subtalar joint during midstance is described by Root et al (1977) as abnormal. It is proposed by them to supinate the midtarsal joint which will create skeletal flexibility within the forefoot, which will result in trauma and injury to the forefoot. However, this and other investigations have used asymptomatic participants which indicate that the relationship between the subtalar joint and midtarsal joint are not how Root et al (1977) described. It also suggests that the movement pattern of the joints within the foot described by this investigation is not a cause of injury.

This investigation, DeMits et al (2012), Leardini et al (2007) and Jenkyn and Nicol (2007) have modelled the navicular and cuboid together as one rigid segment. In contrast, Lundgren et al (2007) and Nester et al (2006) have measured the individual articulations of the bones within the midfoot. As all have reported the same movement pattern, it indicates that the skin based markers can provide some valuable information about how the midfoot is moving during midstance. The results from this investigation also appear to provide a better representation of how the midfoot is moving, than other investigations using skin based markers, when compared to the measurements from intra-cortical bone pins. For example, this investigation, reports that the midfoot dorsiflexed relative to the calcaneus 5.7° (SD

= 2.5°) on the left and 4.3° (SD = 3.8°) on the right during midstance. This is a similar range to Nester et al (2006) and Lundgren et al (2007) who reported that the navicular dorsiflexed relative to the talus up to 10° dorsiflexion, and the cuboid dorsiflexed relative to the calcaneus up to 5° dorsiflexion, during midstance. In contrast, DeMits et al (2012) and Leardini et al (2007) reported less than 1° of dorsiflexion during this phase. The range of frontal and transverse planes motion is more similar and relatively small across all investigations.

At heel lift, the midfoot was not in a maximally pronated position. The results from this investigation demonstrate that the midfoot is in a more everted position relative to the tibia during midstance, than at heel lift. This indicates that the midfoot has inverted from a peak angle of eversion, towards the end of midstance. Although co-incidentally the calcaneus is also in a less everted position relative to the tibia at heel lift than during midstance. This would infer as similar to the midfoot that it is inverting during this phase. This suggests that the relationship between these joints of the foot, are not as Root et al (1977) described. It also indicates that the concurrent inversion of the calcaneus relative to the talus or tibia directly affects the movement of the midfoot and forefoot. As the navicular/cuboid inverted relative to the calcaneus/talus (Wolf et al 2008), and the forefoot inverted relative to the rearfoot (Pohl et al 2006). This suggests that the movement of the bones within this region of the foot are directly affected by the each other, and are coupled. There is considerable inter-participant variation in the position of the midfoot in the sagittal, frontal and transverse planes at heel lift, compared to its movement during midstance. Agreeably, Leardini et al (2007) and DeMits et al (2012) describe how at heel lift there is large inter-participant variation across all planes of motion. For example, DeMits et al (2012) reported standard deviation values in graphical form that range from 5° inverted to 5° everted at heel lift, The graphs displayed in Section 6.3.2 demonstrate a similar pattern and variation. They also emphasise how the mean values cannot represent this amount of inter-participant variation. Overall, the result from this investigation are in agreement with Root et al (1977), , to the extent that agreeably the results from this investigation, and others indicate that the midfoot pronated relative to the calcaneus during midstance. However, it rejects the proposal that the midfoot will be in a maximally pronated position relative to the calcaneus at heel lift.

6.4.6 Root et al Hypothesis 6 - At heel lift the subtalar joint will reach its neutral position

In most feet, the calcaneus was inverted relative to the tibia in NCSP with a mean of 9.2° (SD= 5.0°) on the left, and 9.0° (SD = 5.1°) on the right (Table 6.12).

At heel lift, the calcaneus was everted relative to the tibia with a mean of -0.7° (SD = 4.0°) on the left, and -0.7° (SD = 3.4°) on the right (Table 6.12).

Segment	Plane of motion	Descriptive analysis (+ve angle INV)	Gait Parameter Angle at heel lift Left	Gait Parameter Angle at heel lift Right	Angle at NCSP* Left	Angle at NCSP* Right
Calcaneus-Tibia (left n=90, right n=91)	Frontal (y)	Mean (°)	-0.7	-0.7	9.2	9.0
		SD (°)	*4.0*	3.4	*5.0*	*5.1*
		95% CI (°)	*-1.5- 0.1*	-1.4- 0.03	8.2- 10.3	7.9- 10.1
		No. of feet INV angle (n, %)	*n=39 (43%)*	n=38 (42%)	*n=87 (97%)*	*n=88 (97%)*
		Max INV angle (°)	*8.5*	8.2	*19.5*	*29.1*
		Min INV angle (°)	*0.2*	0.1	*0.3*	*0.6*
		No. of feet EVER angle (n, %)	*n=51 (57%)*	n=53 (58%)	*n=3 (3%)*	*n=3 (3%)*
		Max EVER angle (°)	*-14.4*	-8.2	*-0.9*	*-2.9*
		Min EVER angle (°)	*-0.2*	-0.2	*-0.4*	*-0.1*

Table 6.12 describes the mean frontal plane angle of the calcaneus relative to the tibia at heel lift and in NCSP. The number of feet displaying an INV/EVER angle (n, %). The Max/Min angle of INV/EVER (°).* Measured relative to RCSP which is 0°.

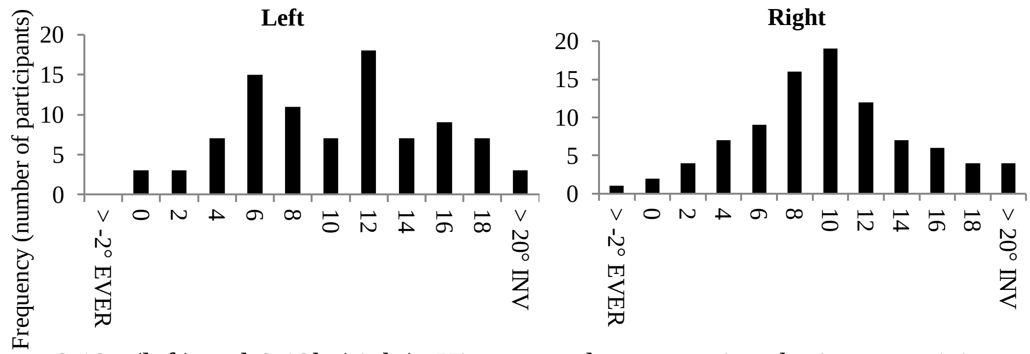


Figure 6.12a (left) and 6.12b (right): Histogram demonstrating the inter-participant variation in the frontal plane angle of the calcaneus relative to the tibia in NCSP. Positive angle: Inverted, Negative angle: Everted

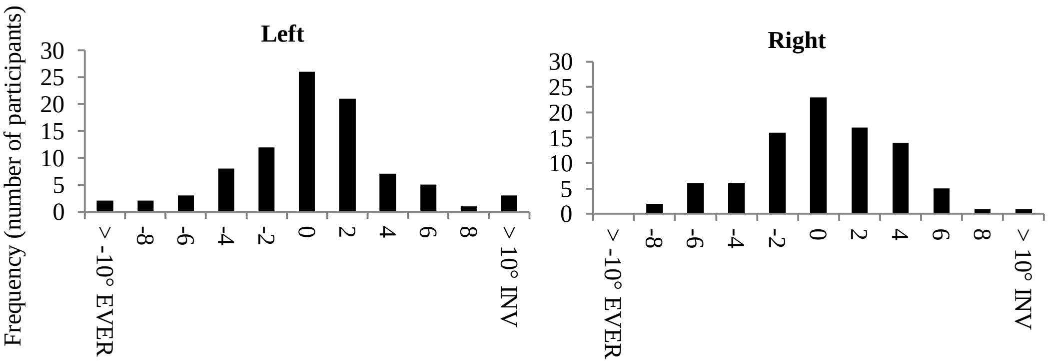


Figure 6.12c (left) and 6.12d (right): Histogram demonstrating the inter-participant variation in the frontal plane angle of the calcaneus relative to the tibia at heel lift. Positive angle: Inverted, Negative angle: Everted

Discussion

The results from this investigation demonstrate that the calcaneus was inverted relative to the tibia in NCSP, and it was everted at heel lift. Therefore, Root et al (1977) would propose that these feet are abnormal, and they do not demonstrate the movement pattern of a normal foot and they will be pre-disposed or present with injury. However, all feet included in this investigation are asymptomatic. Similarity, others (Leardini et al 2007, Cornwall and McPoil 1999a, Kitaoka et al 2006, Hunt et al 2001a, Jenkyn and Nicol 2007, Lundgren et al 2007, Arndt et al 2004 and Rattanaprasert et al 1999) have not measured the position of the subtalar joint when placed in NCSP, all reported that in asymptomatic feet the calcaneus was everted relative to the tibia or talus between -1° to -3° at heel lift.

The zero reference position used to measure any movement, or an angle between two segments in this investigation was defined from RCSP. By positioning the subtalar joint into a neutral position as it is in NCSP from RCSP would therefore result in an inverted or everted angle. This may explain why the calcaneus is inverted in NCSP and no in a neutral position and not in a neutral position. Root et al (1977) hypothesised that in the normal foot, the subtalar joint should be in a neutral position in RCSP, or within 2° everted to 2° inverted. However, the results from this investigation demonstrate that in most feet the calcaneus was inverted relative to the tibia to a much greater than angle than that (Figures 6.12a-6,12b). Figures 6.12a-6.12b demonstrates that only 6 feet were inverted less than 2°. Some (McPoil and Cornwall 1994, McPoil and Cornwall 1996a) have reported a much smaller inverted angle of 1.54° (SD = 3.6°) (McPoil and Cornwall 1994), and 1.2° (SD = 3.7°) (McPoil and Cornwall 1996a) for NCSP. Although, they have used a different technique for the placement of the subtalar joint into a neutral position. Overall, this questions the use of the measurement of the subtalar joint in a neutral position. It strongly indicates that it is not a position used by the foot in static stance, during midstance or at heel lift.

Overall, the results from this investigation are not in agreement with Root et al (1977). . This is because the results from this and other investigations strongly suggest that for a foot to be asymptomatic, the calcaneus relative to the tibia does not need to be in a neutral position at the subtalar joint in NCSP, or pass through this neutral angle at heel lift.,

6.4.7 Root et al Hypothesis 7 - During the phase of propulsion the subtalar joint will be supinating.

The calcaneus inverted (supinated) relative to the tibia during propulsion (left: 9.6° (SD=5.4°) (96% of feet)) (Table 6.14). In all feet, with exception of one foot on the right the calcaneus plantarflexed (left: -22.9° (SD =4.8°), and in most feet adducted (left: -6.6° (SD=4.9°) (91% of feet)) relative to the tibia during propulsion (Table 6.14).

At toe off, in all feet with exception of one the calcaneus was plantarflexed (left: -17.2° (SD=5.3°)), most were inverted (left: 6.8 (SD = 6.4°)) and adducted (left: -1.8° (SD = 5.1°)) relative to the tibia (Table 6.14).

The results presented in Figures 6.13a-6.13f and 6.14a-6.14f demonstrate that although there is inter-participant variation in the range of motion or angle of the calcaneus during this phase, there is consistency in the direction of the motion or angle.

Segment	Plane of Motion	Descriptive analysis (+ve angle/ROM DF, INV,ABD)	Angle at Toe off		ROM during propulsion	
			Left	Right	Left	Right
Calcaneus-Tibia (Left n=99, Right n=100)	Sagittal (x)	Mean (°)	-17.2	-16.3	-22.9	-21.9
		SD (°)	5.3	5.3	4.8	4.4
		95% CI (°)	-18.3- -16.1	-18.2- -16.1	-23.9- -21.9	-22.8- -21.1
		No. of feet DF angle/ROM (n, %)	0	n=1 (1%)	0	0
		Max DF angle/ ROM (°)	-	0.4	-	-
		Min DF angle/ ROM (°)	-	-	-	-
		No. of feet PF angle/ROM (n, %)	n=99 (100%)	n=99 (99%)	n=99 (100%)	n=100 (100%)
		Max PF angle/ ROM(°)	-33.0	-34.4	-37.9	-33.1
		Min PF angle/ ROM (°)	-5.0	-5.8	-12.1	-11.2
	Frontal (y)	Mean (°)	6.8	9.1	9.6	11.1
		SD (°)	6.4	5.1	5.4	3.8
		95% CI (°)	5.5- 8.1	8.1- 10.1	8.5- 10.7	10.3- 11.8
		No. of feet INV angle/ROM (n, %)	n=89 (90%)	n=96 (96%)	n=95 (96%)	n=99 (99%)
		Max INV angle/ ROM (°)	30.9	23.4	30.7	20.2
		Min INV angle/ ROM (°)	0.5	0.3	3.7	2.9
		No .of feet EVER angle/ROM (n,%)	n=10 (10%)	n=4 (4%)	n=4 (4%)	n=1 (1%)
		Max EVER angle/ROM(°)	-12.6	-6.4	-15.7	-3.0
		Min EVER angle/ ROM (°)	-0.2	-0.4	-4.2	-
	Transverse (z)	Mean (°)	-1.8	-3.8	-6.6	-7.9
		SD (°)	5.1	4.5	4.9	53.4
		95% CI (°)	-2.8- -0.8	-4.7- -2.9	-7.6- -5.6	-8.6- -7.3
		No. of feet ABD angle/ROM (n, %)	n=37 (37%)	n=19 (19%)	n=9 (9%)	0
		Max ABD angle/ROM(°)	11.8	14.2	9.3	-
		Min ABD angle/ ROM (°)	0.1	0.1	0.2	-
		No. of feet ADD angle/ROM (n, %)	n=62 (63%)	n=81 (81%)	n=90 (91%)	n=100 (100%)
		Max ADD angle/ ROM (°)	-18.2	-16.4	-18.5	-18.9
		Min ADD angle/ ROM (°)	-0.1	-0.3	-2.2	-2.8

Table 6.13 describes the mean range of sagittal, frontal and transverse plane motion and angle of the calcaneus relative to the tibia during propulsion and at toe off. The number of feet displaying range or angle of DF/PF, INV/EVER, ABD/ADD (n, %). The Max/Min range or angle of DF/PF, INV/EVER, ABD/ADD (°).

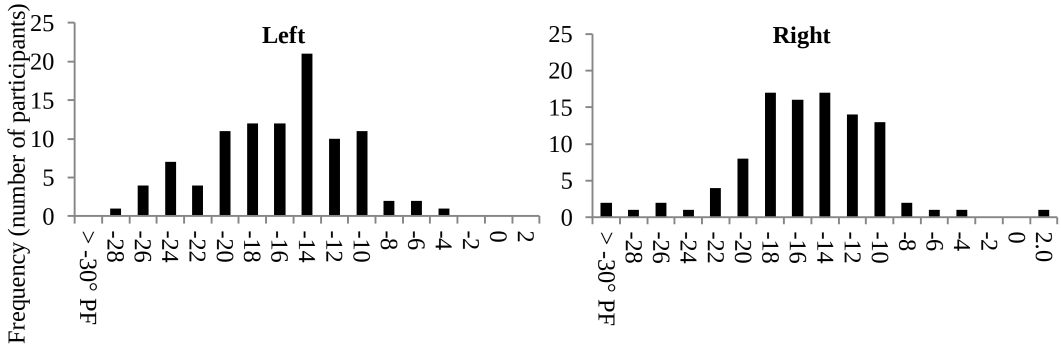


Figure 6.13a (left) and 6.13b (right): Histogram demonstrating the inter-participant variation in the sagittal plane angle of the calcaneus relative to the tibia at toe off. Positive angle: Dorsiflexed, Negative angle: Plantarflexed.

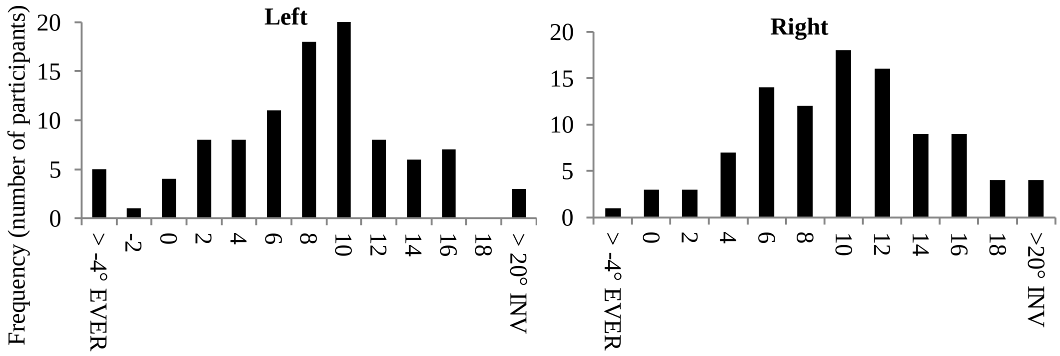


Figure 6.13c (left) and 6.13d (right): Histogram demonstrating the inter-participant variation in the frontal plane angle of the calcaneus relative to the tibia at toe off. Positive angle: Inverted, Negative angle: Everted.

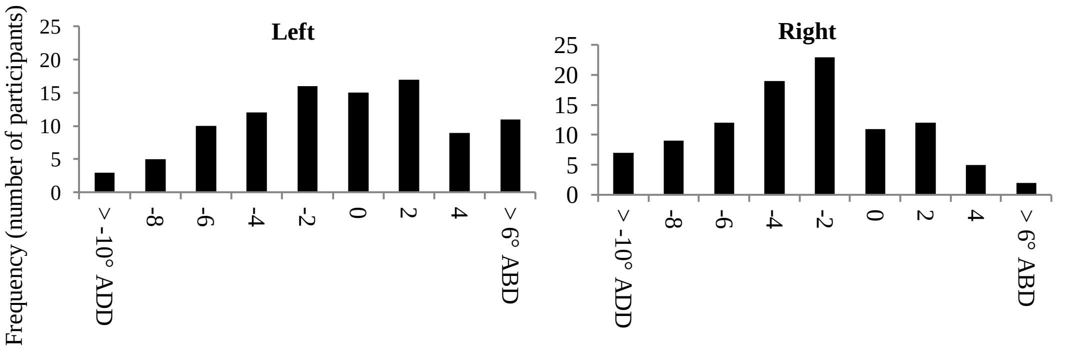


Figure 6.13e (left) and 6.13f (right): Histogram demonstrating the inter-participant variation in the transverse plane angle of the calcaneus relative to the tibia at toe off. Positive angle: Abducted, Negative angle: Adducted.

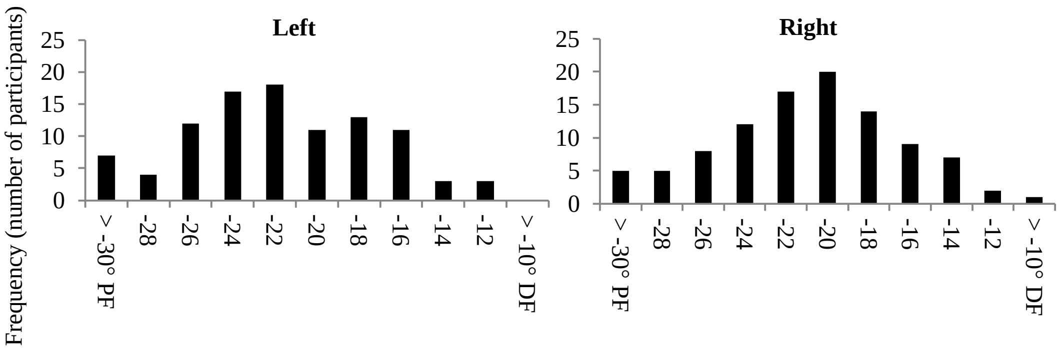


Figure 6.14a (left) and 6.14b (right): Histogram demonstrating the inter-participant variation in the range of sagittal plane motion of the calcaneus relative to the tibia during propulsion. Positive range of motion: Dorsiflexion, Negative range of motion: Plantarflexion

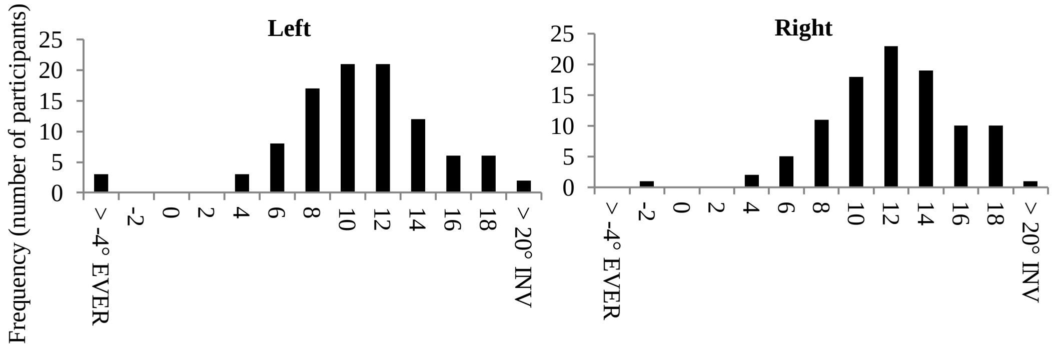


Figure 6.14c (left) and 6.14d (right): Histogram demonstrating the inter-participant variation in the range of frontal plane motion of the calcaneus relative to the tibia during propulsion. Positive range of motion: Inversion, Negative range of motion: Eversion

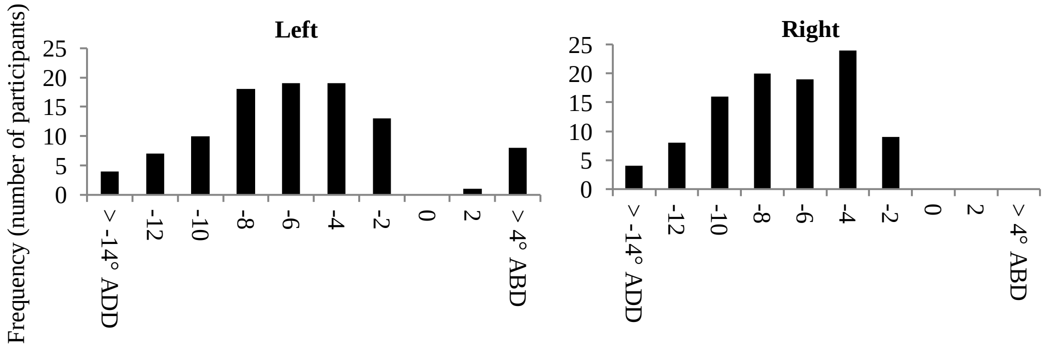


Figure 6.14e (left) and 6.14f (right): Histogram demonstrating the inter-participant variation in the range of transverse plane motion of the calcaneus relative to the tibia during propulsion. Positive range of motion: Abduction, Negative range of motion: Adduction.

Discussion

Supination of the subtalar joint during propulsion was described by Root et al (1977) as a key determinant of the proposed normal function of the foot during the gait cycle. They hypothesised that it would ensure that the foot would remain a stable, and rigid lever as the heel lifted from the ground. The results from this investigation and others (Hunt et al 2001a, Leardini et al 2007, Cornwall and McPoil 1999a, Kitaoka et al 2006, Moseley et al 1996, Lundgren et al 2007, Arndt et al 2004, Simon et al 2006, Jenkyn and Nicol 2007) which have all used asymptomatic participants, report in agreement with Root et al (1977) that the calcaneus inverted relative to tibia (or talus) during propulsion, and was in an inverted position at toe off. Therefore, indicating that the subtalar joint is supinating during this phase and is in a supinated angle at toe off.

The range of inversion reported by this investigation is similar to those previously referred to who have used skin mounted markers as they report between 8° and 11° of inversion during propulsion. Lundgren et al (2007) and Arndt et al (2004) who have measured the calcaneus relative to the talus with intra-cortical bone pins reported a considerably smaller range of only 5° inversion. Although, both Lundgren et al (2007) and Arndt et al (2004) reported that the talus inverted relative to the tibia during propulsion and therefore the movement of this articulation is included when measuring the movement of the calcaneus relative to the tibia. This could have contributed to the increased range of inversion measured in this and other investigations that have measured the calcaneus relative to the tibia. This also indicates that contrary to what Root et al (1977) hypothesised, the ankle joint does not purely function in the sagittal plane.

Supination of the subtalar joint is a tri-planar motion and when weight bearing, Root et al (1977) proposed that with inversion of the calcaneus, the talus would dorsiflex and abduct upon the calcaneus. However, as the heel lifts from the ground the calcaneus could now be assumed to be non-weight bearing, and therefore will move in what Root et al (1977) described as open-chain supination. This includes plantarflexion, inversion and adduction of the calcaneus relative to the talus. A limitation of this investigation is that is unable to measure talar motion, and therefore cannot confirm whether the talus is moving as Root et al (1977) during this phase.

In the sagittal plane, this investigation and others (Hunt et al 2001a, Leardini et al 2007, Cornwall and McPoil 1999a, Kitaoka et al 2006, Jenkyn and Nicol 2007, Moseley et al 1996) report that in agreement with Root et al (1977) the calcaneus plantarflexed relative to the tibia during propulsion, and was in a plantarflexed angle at toe off. This investigation, and others that have used skin mounted markers report a much greater sagittal plane movement, and angle of the calcaneus relative to the tibia, than those (Arndt et al 2004, Lundgren et al 2007, Nester et al 2006) that have measured the calcaneus relative to the talus with intra-cortical bone pins. This indicates that the ankle joint is the primary contributor to sagittal plane motion occurring between the calcaneus relative to the tibia during propulsion.

In the transverse plane, this investigation and others (Rattanaprasert et al 1999, Leardini et al 2007, Moseley et al 1996) report an overall mean value indicating that the calcaneus adducted relative to the tibia during propulsion, and is in an adducted angle at toe off.. In contrast, Cornwall and McPoil (1999a), Kitaoka et al (2006), and Hunt et al (2001a) reported that the calcaneus abducted relative to the tibia during propulsion, and was in an abducted position at toe off. However, this investigation, Lundgren et al (2007), Arndt et al (2004) and Leardini et al (2007) report large inter-participant variation in the angle of the calcaneus relative to the tibia at toe off. In all of the previously discussed literature, they all described that there was a similar number of feet that were in an abducted, or adducted position at toe off.

Overall, the results from this investigation are in agreement with the Root et al (1977) description. This is because in the majority of feet, the calcaneus inverted, plantarflexed, and adducted relative to the tibia during propulsion which indicates in agreement with Root et al (1977) that the subtalar joint will be supinating during this phase.

6.4.8 Root et al Hypothesis 8 - During the phase of propulsion, the midtarsal joint will remain in a pronated position (everted) around the longitudinal axis, and it will supinate (plantarflex and adduct) around the oblique axis.

The mean results demonstrate that in most feet the midfoot inverted (right: 2.6° (SD=2.8°) 82% of feet), plantarflexed (right: -4.7° (SD=4.3°) 81% of feet) and adducted (right: -3.9° (SD=2.2°) 97% of feet) relative to the calcaneus during propulsion. There are similar values for the left.

The results presented in Figures 6.15a-6.15f demonstrate that although there is inter-participant variation in the range of motion of the midfoot during this phase, there is consistency in the direction of the motion. With exception of the left, as the midfoot inverted relative to the calcaneus in 54% of feet, but the mean value suggests eversion (left: -0.1° (SD=3.9°)). The 95% confidence interval is inclusive of inversion and eversion values (left: -0.8°- 0.7°).

Segment	Plane of Motion	Descriptive analysis (+ve ROM DF, INV, ABD)	ROM during propulsion	
			Left	Right
Midfoot-Calcaneus (Left n=99, Right n=95)	Sagittal (x)	Mean (°)	-2.6	-4.7
		SD (°)	*3.9*	*4.3*
		95% CI (°)	*-3.4- -1.6*	*-5.5- -3.8*
		No. of feet DF ROM (n, %)	*n=28 (29%)*	*n=14 (15%)*
		Max DF ROM (°)	*8.5*	*7.9*
		Min DF ROM (°)	*1.9*	*1.8*
		No. of feet PF ROM (n, %)	*n=71 (72%)*	*n=81 (85%)*
		Max PF ROM (°)	*-12.9*	*-12.7*
		Min PF ROM (°)	*-2.1*	*-1.9*
	Frontal (y)	Mean (°)	-0.1	2.6
		SD (°)	*3.9*	*2.8*
		95% CI (°)	*-0.8- 0.7*	*2.1- 3.2*
		No. of feet INV ROM (n, %)	*n=53 (54%)*	*n=82 (86%)*
		Max INV ROM (°)	*8.9*	*8.2*
		Min INV ROM (°)	*1.0*	*1.1*
		No. of feet EVER ROM (n, %)	*n=46 (46%)*	*n=13 (14%)*
		Max EVER ROM (°)	*-9.3*	*-4.7*
		Min EVER ROM (°)	*-1.5*	*-0.9*
	Transverse (z)	Mean (°)	-1.8	-3.9
		SD (°)	*2.7*	*2.2*
		95% CI (°)	*-2.4- -1.3*	*-4.4- -3.5*
		No. of feet ABD ROM (n, %)	*n=26 (26%)*	*n=3 (3%)*
		Max ABD ROM (°)	*4.0*	*2.9*
		Min ABD ROM (°)	*1.0*	*1.2*
		No .of feet ADD ROM (n, %)	*n=73 (74%)*	*n=92 (97%)*
		Max ADD ROM (°)	*-7.1*	*-11.4*
		Min ADD ROM (°)	*-0.9*	*-1.3*

Table 6.14 describes the mean plane range of sagittal, frontal and transverse plane motion of the midfoot relative to the calcaneus during propulsion. The number of feet displaying range of DF/PF, INV/EVER, ABD/ADD (n, %). The Max/Min range of DF/PF, INV/EVER, ABD/ADD (°).

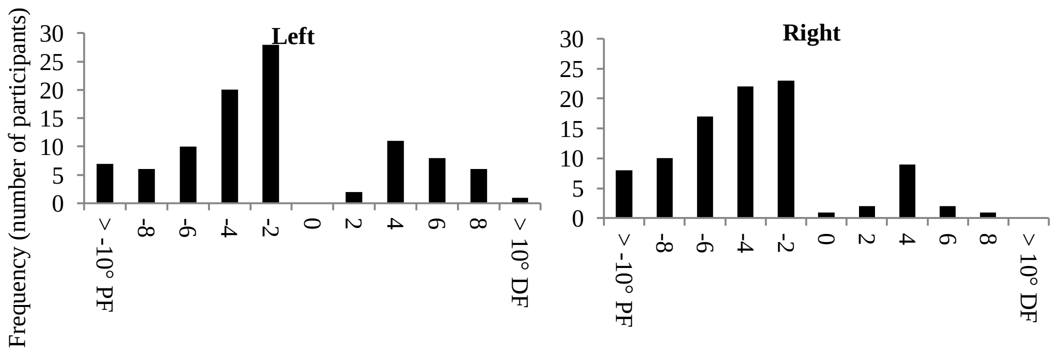


Figure 6.15a (left) and 6.25b (right): Histogram demonstrating the inter-participant variation in the range of sagittal plane motion of the midfoot relative to the calcaneus during propulsion. Positive range of motion: Dorsiflexion, Negative range of motion: Plantarflexion.

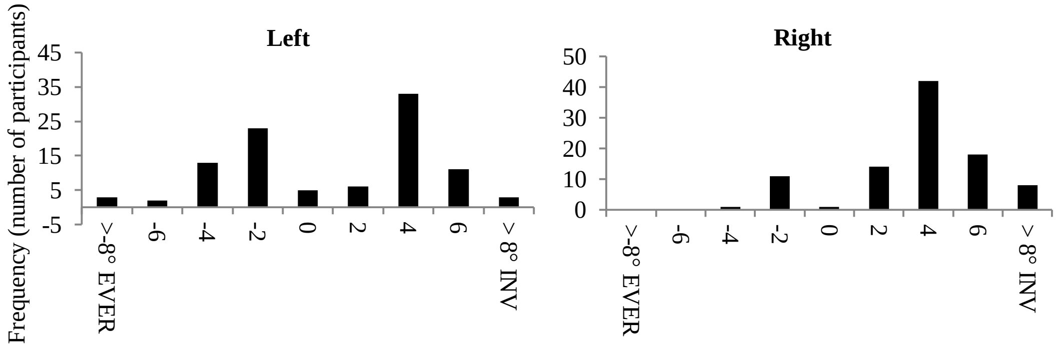


Figure 6.15c (left) and 6.15d (right): Histogram demonstrating the inter-participant variation in the range of frontal plane motion of the midfoot relative to the calcaneus during propulsion. Positive range of motion: Inversion, Negative range of motion: Eversion.

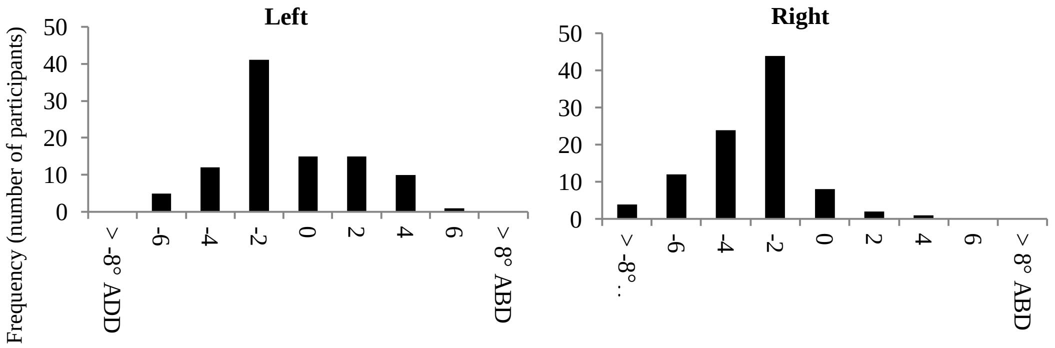


Figure 6.15e (left) and 6.15f (right): Histogram demonstrating the inter-participant variation in the range of transverse plane motion of the midfoot relative to the calcaneus during propulsion. Positive range of motion: Abduction, Negative range of motion: Adduction.

Discussion

Root et al (1977) proposed that the opposing movements of the midtarsal joint around its oblique, and longitudinal axes during propulsion are vital for the normal function of the foot. They hypothesised that it will ensure the foot will remain stable, and allow for the transfer of load from lateral, to medial across the forefoot as the heel lifts from the ground. Root et al (1977) stated that the midtarsal joint will remain in a pronated position, and effectively a locked or non-moving position around the longitudinal axis and it will supinate around the oblique axis. Root et al (1977) hypothesised that supination around the longitudinal axis of the midtarsal joint will create mobility within the foot. They described how the foot will resemble a mobile adapter and be pre-disposed to, or present with injury.

The results from this investigation and others (Leardini et al 2007, DeMits et al 2012, Lundgren et al 2007, Nester et al 2006) demonstrate that contrary to Root et al (1977) the midfoot (or the navicular and cuboid) inverted relative to the calcaneus or talus. Although during propulsion it did plantarflex and adduct. This investigation and the others previously referred to have all used asymptomatic participants. This indicates that the movement of the midfoot described here is not a cause of injury. There is a clear trend in the movement of the midfoot relative to the calcaneus across all planes of motion reported by this and other (Leardini et al 2007, DeMits et al 2012, Lundgren et al 2007, Nester et al 2006) investigations, which is not discussed by Root et al (1977). For the first half of propulsion, the range of motion was relatively small, and then the midfoot (or the navicular and cuboid) rapidly plantarflexed, inverted and adducted.

The range of sagittal, frontal and transverse plane motion of the midfoot relative to the calcaneus reported by this investigation is similar to those (Leardini et al 2007 and DeMits et al 2012) that have measured the midfoot as an individual rigid segment. For example, in the sagittal plane, the range of plantarflexion in this investigation (left: -2.6° (SD =3.9°), right: -4.7° (SD = 4.3°)), compares well to DeMits et al (2012) (-3°) and Leardini et al (2007) (-2°). However, Lundgren et al (2012) and Nester et al (2006) measured the individual movements of the navicular and cuboid. They reported that the navicular plantarflexed 10° relative to the talus, and the cuboid plantarflexed 5° relative to the calcaneus during propulsion. There is a similar difference in the range of frontal, and transverse plane motion between investigations using either method. This suggests that the navicular and cuboid move independently to each other during this phase. This individual movements within the midfoot would not be able to be represented by this investigation or those (Leardini et al 2007, DeMits et al 2012) that have defined the midfoot as one rigid segment. This is a key limitation of this investigation, and others who have attempted to measure midfoot kinematics from skin mounted markers.

The rigid segment definition of the midfoot used in this investigation compares well to Root et al (1977) description of the midtarsal joint. This is because they too described the navicular and cuboid as one functional unit that moves relative to the talus and calcaneus. However, the results from those (Hunt et al 2001, Rattanaprasert et al 1999, Kitaoka et al 2006) that have measured the movement of forefoot relative to the calcaneus appear to provide a more similar description to Root et al (1977), than this investigation and those measuring the midfoot as its own rigid segment. The measurement of the forefoot relative to the rearfoot is also more similar to Root et al (1977) description of the static examination of the range of motion of the midtarsal joint, through measurement of the angle of the forefoot to rearfoot relationship. All investigations (Hunt et al 2001a, Rattanaprasert et al 1999, Kitaoka et al 2006) reported that the forefoot everted relative to the rearfoot during propulsion. This would comply with Root et al (1977) description of pronation around the longitudinal axis of the midtarsal joint. Although, the results from these investigations indicate that the forefoot continued to evert relative to the calcaneus throughout propulsion, and was not as Root et al (1977) proposed in a locked everted position.

This measurement of the forefoot to rearfoot relationship is in consideration of the complexity of the midfoot region, a poor representation of the intricate mechanics of the joints within it. This is highlighted by the results from Leardini et al (2007) who reported inversion of the midfoot relative to the calcaneus, but eversion of the forefoot relative to the calcaneus. Therefore, emphasising that the movement of the midfoot should be measured in its own entity. A possible explanation of why there is a difference in the results between investigations which have used different methods for measuring midfoot kinematics maybe because of the articulation between the navicular and cuboid with the metatarsals. Those (Leardini et al 2007, DeMits et al 2012), including this investigation define the midfoot as a rigid segment. Therefore the aim is to only measure the movement of the navicular and cuboid relative to the calcaneus. While others (Hunt et al 2001a, Rattanaprasert et al 1999, Kitaoka et al 2006), which measure the forefoot as one rigid segment incorporate the movement of the metatarsals relative to the navicular and cuboid, and then those relative to the calcaneus. The results from this investigation and Lundgren et al (2007) indicate that the metatarsals move in a different direction and greater range of motion than the midfoot during propulsion. There are several difficulties with Root et al (1977) description of how the movement of the midtarsal joint is controlled during propulsion. They proposed that supination of the subtalar joint and additional control provided by some extrinsic muscles of the foot, mainly peroneus longus, peroneus brevis and soleus. These will maintain the midtarsal joint pronated around its longitudinal axis, and supinate it around its oblique axis. Agreeably, Ivanenko et al (2004) reported that these muscles are active during propulsion. However, the insertion site of peroneus longus is onto the head of the first metatarsal, and the peronues brevis inserts onto the base of the fifth metatarsal. Therefore their anatomical pathways would exert little influence on midfoot kinematics, and instead help to evert the forefoot. The results from Hypothesis 7 (Section 6.4.7) demonstrate that the subtalar joint will supinate during propulsion.

However, the results from Hypothesis 5 (Section 6.4.5) also suggest that the relationship between the subtalar and midtarsal joints are not as Root et al (1977) described. This is again demonstrated here, as with supination of the subtalar joint the midfoot inverted, and did not remain in an everted position as Root et al (1977) proposed.

Overall, the results from this investigation are not in agreement with the Root et al (1977) description. This is because contrary to Root et al (1977) the midfoot inverted relative to the calcaneus during propulsion and all feet included in this investigation are asymptomatic. In a comparison of different methods for measuring midfoot kinematics, it would suggest that Root et al (1977) description pertains more to the movement of the forefoot relative to the calcaneus, rather than the midfoot itself.

6.4.9 Root et al Hypothesis 9 - The first metatarsophalangeal joint will dorsiflex between 65°-75° during propulsion.

The hallux was not dorsiflexed more than 65° relative to the medial forefoot at the angle of toe off (left: 33.2° (SD=9.8°), or the peak angle of dorsiflexion during propulsion (left: 44.9° (SD=8.7°) (Table 6.15). One foot on the left, and right dorsiflexed more than 65° for either of the gait parameters tested (Figures 6.16a-6.16b and 6.17a-6.17b).

There was large inter-participant variation reported across all gait parameters tested with standard deviation values (left: SD= >8.7°, right: SD= >11.8°), and a great variation in the maximum and minimum values (left: Max DF angle: 75.9°, Min DF angle: 26.1°) (Table 6.15) (Figures 6.16a-6.16b and 6.17a-6.17b).

Segment	Descriptive analysis (+ve angle DF)	Peak angle of DF during propulsion		Angle at toe off	
		Left	Right	Left	Right
Hallux-Medial FF Left n=99, Right n=95	Mean (°)	44.9	46.9	33.2	34.6
	SD (°)	*8.7*	*11.8*	*9.8*	*13.5*
	95% CI (°)	*43.3- 46.7*	*44.6- 49.4*	*31.2- 35.1*	*31.8- 37.3*
	Max DF angle (°)	*75.9*	*72.4*	*69.0*	*66.4*
	Min DF angle (°)	*26.1*	*14.9**	*15.5*	*0.1**

Table 6.15 describes the mean sagittal angle of the hallux relative to the medial forefoot at toe off and the peak angle of dorsiflexion during propulsion. The number of feet displaying an angle of DF (n, %). The Max/Min range or angle of DF (°). * No. of feet that demonstrate a plantarflexed angle at toe off right: 1/95

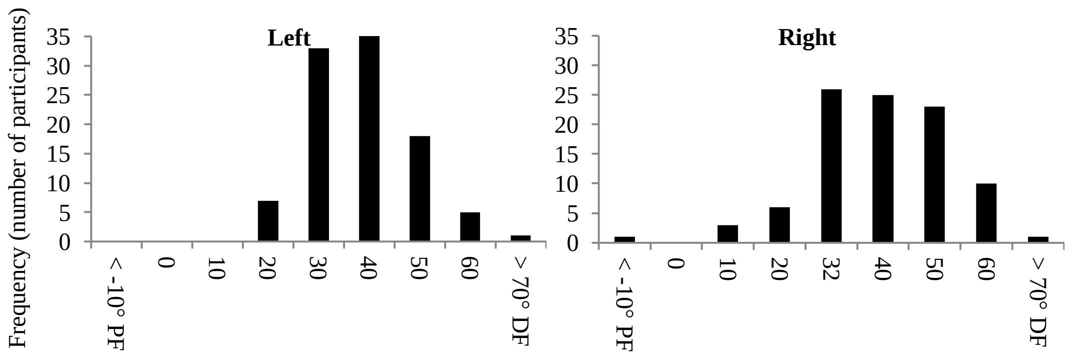


Figure 6.16a (left) and 6.16b (right): Histogram demonstrating the inter-participant variation in the sagittal plane angle of the hallux relative to the medial forefoot at toe off. Positive angle: Dorsiflexed, Negative angle: Plantarflexed.

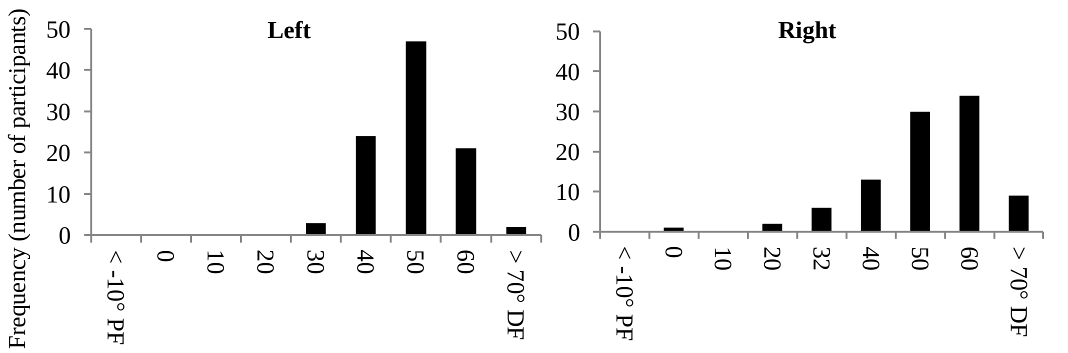


Figure 6.17a (left) and 6.17b (right): Histogram demonstrating the inter-participant variation in the peak angle of dorsiflexion of the hallux relative to the medial forefoot during propulsion. Positive angle: Dorsiflexed, Negative angle: Plantarflexed.

Discussion

Root et al (1977) proposed that in the normal foot the first metatarsophalangeal joint will dorsiflex during propulsion to an angle of at least 65°during propulsion, or at toe off. However, the results from this investigation, and many others (Halstead and Redmond 2006, Nawoczenski et al 1999, DeMits et al 2012, Carson et al 2001, Turner et al 2007, Simon et al 2006, Van Gheluwe et al 2006) demonstrate that the hallux was not dorsiflexed to 65° relative to the first metatarsal/medial forefoot at toe off or during propulsion. This investigation reports that the peak angle of hallux dorsiflexion relative to the medial forefoot during propulsion was 44.9° (SD =8.7°) on the left, and 46.9° (SD = 11.8°) on the right. This is a similar to that reported by others (Halstead and Redmond 2006, Nawoczenski et al 1999, Simon et al 2006, DeMits et al 2012, Carson et al 2001) who report that the peak angle of hallux dorsiflexion relative to the medial forefoot was between 36.0° to 48.0° during propulsion.

There is considerable inter-participant variation in the angle of the hallux relative to the medial forefoot during propulsion and at toe off. This can be demonstrated by the large standard deviation (or standard error of the mean) values reported by this and all investigations. By grouping the data, it helps to emphasise how variable the angle of dorsiflexion at the first metatarsophalangeal joint is between participants. For example on the left at the peak angle of dorsiflexion during propulsion the number of feet dorsiflexed to between 0° to 30° is n = 3, between 31°- 40° is n = 24, between 40° to 50° is n = 47, between 50° to 65° is n = 22 and more than 65° is n = 3 on the left. Similar values were reported for the right. This strongly indicates that contrary to Root et al (1977), and as similar for other joints within the foot, it is not possible to stipulate a specific angle at a joint that should be determined to represent the normal foot. As the cohort of participants used in this investigation is much larger than those investigations previously referred to the variation between participants can be considered to reflect the broader population. Root et al (1977) proposed that if the first metatarsophalangeal joint is unable to dorsiflex to 65° during propulsion, there is a structural deformity of this joint, which is probably caused by abnormal pronation of the subtalar joint. Agreeably, this investigation reports that in most feet the calcaneus everted relative to the tibia during midstance (Hypothesis 4 (Section 6.4.4)). Root et al (1977) would classify this as abnormal movement of the foot. However, in most feet, the calcaneus inverted, to represent supination during propulsion as demonstrated by Hypothesis 7 (Section 6.4.7). Thus, supination of the subtalar joint appeared to concur with dorsiflexion of the first metatarsophalangeal joint. All feet included in this and all other (Halstead and Redmond 2006, Nawoczenski et al 1999, DeMits et al 2012, Carson et al 2001, Turner et al 2007, Simon et al 2006) investigations are asymptomatic, and all are from visual inspection free of deformity to the first metatarsophalangeal joint.

A limitation of this investigation and others (Halstead and Redmond 2006, Nawoczenski et al 1999, DeMits et al 2012, Carson et al 2001, Turner et al 2007, Simon et al 2006) is that no radiographic or ultrasound imaging is presented. This would confirm whether there are any structural changes at the first metatarsophalangeal joint, or changes to the soft tissues surrounding it in the participants assessed. However, Lorimer et al (2002) described how a clinical based examination should provide sufficient information. This is because the small soft tissue structures, and little adipose tissue that surround this area of the foot would make any swelling, or changes in the bony architecture of the joint visible from the skins surface. A second limitation of this investigation is that for the measurement of the first metatarsophalangeal joint, the first metatarsal is defined as the medial forefoot. This was used because it is difficult to distinguish the exact shape of the first metatarsal on its lateral aspect from the skin surface. The small anatomical shape of the first metatarsal also makes it difficult to ensure there is enough space between markers to avoid cross-marker interference. This would significantly affect the quality of the data collected. However, to reduce possible interference caused by motion of the second metatarsal or surrounding soft tissue structures, the plastic plate was positioned on the medial aspect of the first metatarsal, and it is elevated from the foot on the lateral aspect.

A third limitation is that because of the small size of the proximal phalange of the hallux it was difficult to ascertain the exact shape of it, and secure the hallux foot plate directly over it. Therefore, there may have been movement incurred under the hallux plate from inter-phalangeal movement within the hallux. This would suggest the segment measured is not rigid. However, by attaching the markers to a plastic rigid plate as this investigation used it aimed to provide as suitable as possible definition of a rigid segment. Others (Simon et al 2006, Carson et al 2001, MacWilliams et al 2003, DeMits et al 2012), have used individual markers attached along the hallux to represent it as one rigid segment. Such methods would be much more susceptible to within segment movement and provide a poor definition of a rigid segment.

Overall, the results from this investigation are not in agreement with the Root et al (1977) description. This is because as the results from this, and other investigations demonstrate that in asymptomatic feet the hallux was not dorsiflexed to 65° relative to the medial forefoot/first metatarsal at toe off or during propulsion.

6.4.10 Root et al Hypothesis 10 - During the swing phase the subtalar joint will supinate, and the midtarsal joint will supinate around its longitudinal axis.

The calcaneus dorsiflexed (left: 19.5° (SD = 5.2°)) in all feet, everted (left: -5.1° (SD = 7.8°), and abducted (left: 3.3° (SD = 8.5°) in most feet relative to the tibia during the swing phase (Table 6.16). There is greater inter-participant variation on the left in the transverse plane as in only 67% of feet the calcaneus abducted relative to the tibia, compared to 94% on the right. This may have contributed to why the mean value is smaller than on the left.

The midfoot inverted (supinated) (left: 3.1° (SD =7.8°) 76% of feet) relative to the calcaneus in the majority of feet during the swing phase. The mean values indicate that the midfoot plantarflexed (left: -1.8° (SD=7.9°) and abducted (left: 3.3° (SD = 8.5°)) relative to the calcaneus during the swing phase. There is some inter-participant variation in the direction of motion, much more so than for the calcaneus relative to the tibia (Figure 6.18a-6.18f and 6.19a-6.19f). On the left, the midfoot plantarflexed in 63% of feet, inverted in 76% of feet and adducted in 53% of feet relative to the calcaneus during the swing phase. There is similar variation on the right.

Plane of motion	Descriptive analysis (+ve ROM DF, INV, ABD)	ROM during swing phase			
		Calcaneus-Tibia		Midfoot-Calc	
		Left (n=98)	Right (n=100)	Left (n=94)	Right (n=94)
Sagittal (x)	Mean (°)	19.5	18.7	-1.8	-1.3
	SD (°)	5.2	7.3	7.9	5.3
	95% CI (°)	18.4- 20.5	17.8- 19.6	-3.4- -0.1	-2.4- -0.2
	No. of feet DF ROM (n, %)	n=98 (100%)	n=100 (100%)	n=35 (37%)	n=38 (40%)
	Max DF ROM(°)	34.4	19.4	27.7	7.8
	Min DF ROM (°)	8.4	7.3	1.6	1.6
	No. of feet PF ROM (n, %)	0	0	n=59 (63%)	n=56 (60%)
	Max PF ROM (°)	-	-	-16.3	-7.5
	Min PF ROM (°)	-	-	-0.4	-0.1
Frontal (y)	Mean (°)	-5.1	-7.9	3.1	2.5
	SD (°)	7.8	4.4	4.6	3.9
	95% CI (°)	-6.7- -3.5	-8.8- -7.0	2.1- 4.0	1.7- 3.3
	No. of feet INV ROM (n, %)	n=27 (27%)	n=7 (7%)	n=71 (76%)	n=75 (80%)
	Max INV ROM (°)	11.8	4.6	11.9	12.2
	Min INV ROM (°)	2.2	2.6	1.9	1.0
	No .of feet EVER ROM (n,%)	n=71 (73%)	n=93 (93%)	n=23 (24%)	n=19 (20%)
	Max EVER ROM (°)	-20.8	-19.5	-6.7	-8.2
	Min EVER ROM (°)	-4.4	-2.9	-2.3	-1.2
Transverse (z)	Mean (°)	3.3	8.2	0.5	2.3
	SD (°)	8.5	4.8	4.0	2.9
	95% CI (°)	1.6- 5.0	7.2- 9.1	-0.3- 1.3	1.7- 2.9
	No. of feet ABD ROM (n, %)	n=66 67%)	n=94 (94%)	n=50 (53%)	n=75 (80%)
	Max ABD ROM (°)	17.5	18.1	9.1	10.3
	Min ABD ROM (°)	4.3	4.1	1.0	1.5
	No .of feet ADD ROM (n, %)	n=32 (33%)	n=6 (6%)	n=44 (47%)	n=19 (20%)
	Max ADD ROM (°)	-11.6	-13.7	-7.8	-4.4
	Min ADD ROM (°)	-3.2	-3.7	-1.5	-0.95

Table 6.16 describes the mean range of sagittal, frontal and transverse plane motion of the calcaneus relative to the tibia and the midfoot relative to the calcaneus during the swing phase. The number of feet displaying range of DF/PF, INV/EVER, ABD/ADD (n, %). The Max/Min range of DF/PF, INV/EVER, ABD/ADD (°).

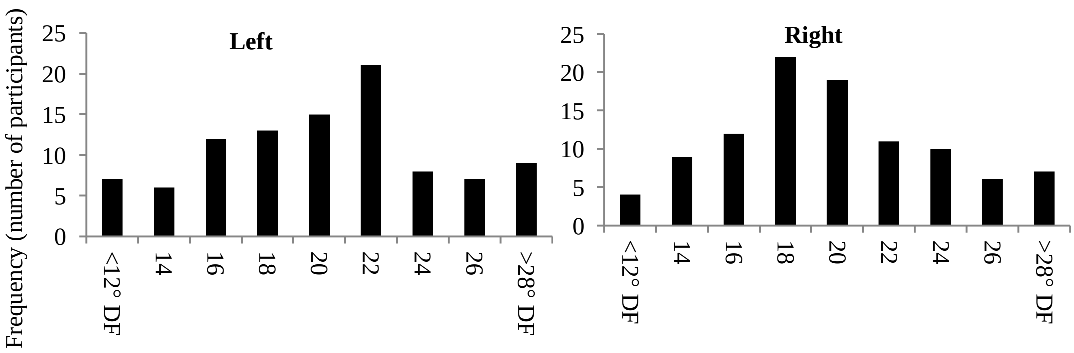


Figure 6.18a (left) and 6.18f (right): Histogram demonstrating the inter-participant variation in the range of sagittal plane motion of the calcaneus relative to the tibia during the swing phase. Positive range of motion: Dorsiflexion, Negative range of motion: Plantarflexion.

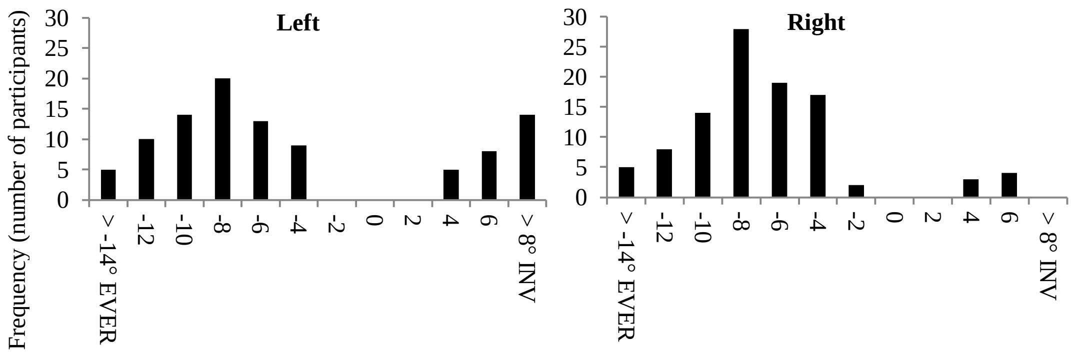


Figure 6.18c (left) and 6.18d (right): Histogram demonstrating the inter-participant variation in the range of frontal plane motion of the calcaneus relative to the tibia during the swing phase. Positive range of motion: Inversion, Negative range of motion: Eversion.

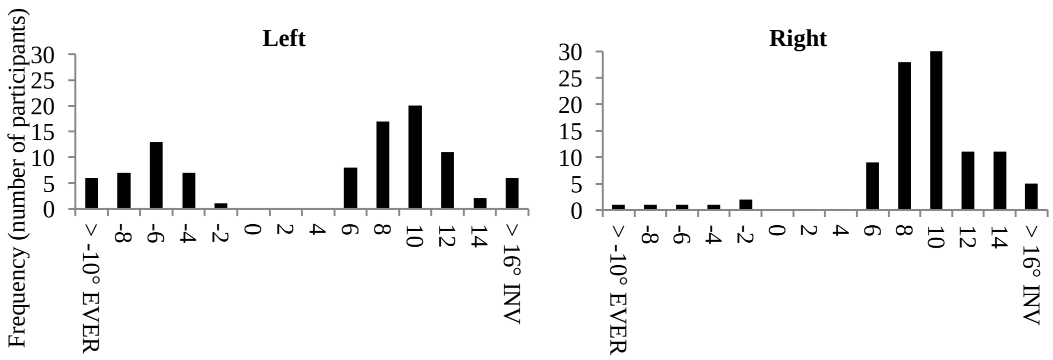


Figure 6.18e (left) and 6.18f (right): Histogram demonstrating the inter-participant variation in the range of transverse plane motion of the calcaneus relative to the tibia during the swing phase. Positive range of motion: Abduction, Negative range of motion: Adduction.

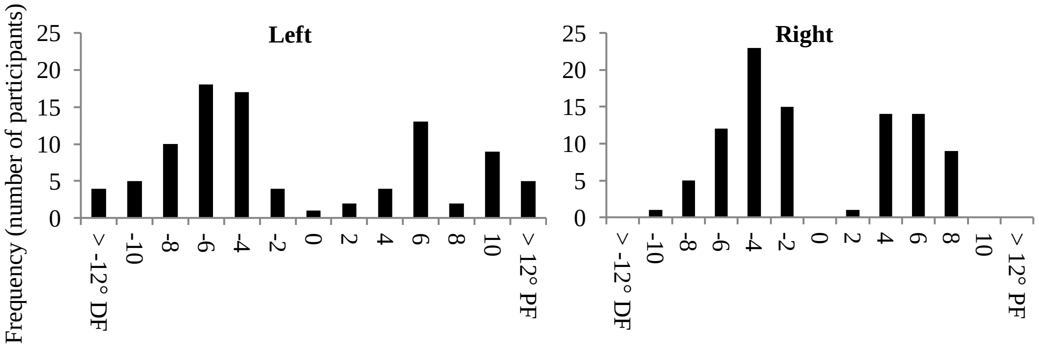


Figure 6.19a (left) and 6.19b (right): Histogram demonstrating the inter-participant variation in the range of sagittal plane motion of the midfoot relative to the calcaneus during the swing phase. Positive range of motion: Dorsiflexion, Negative range of motion: Plantarflexion.

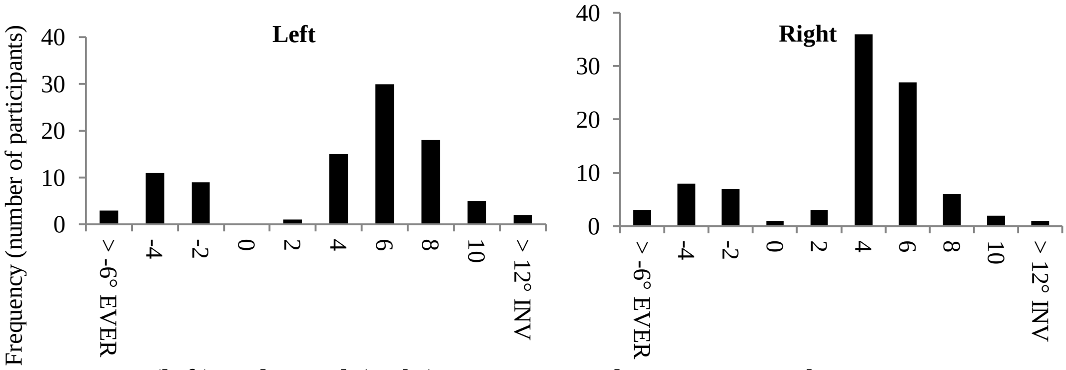


Figure 6.19c (left) and 6.19d (right): Histogram demonstrating the inter-participant variation in the range of frontal plane motion of the midfoot relative to the calcaneus during the swing phase. Positive range of motion: Inversion, Negative range of motion: Eversion.

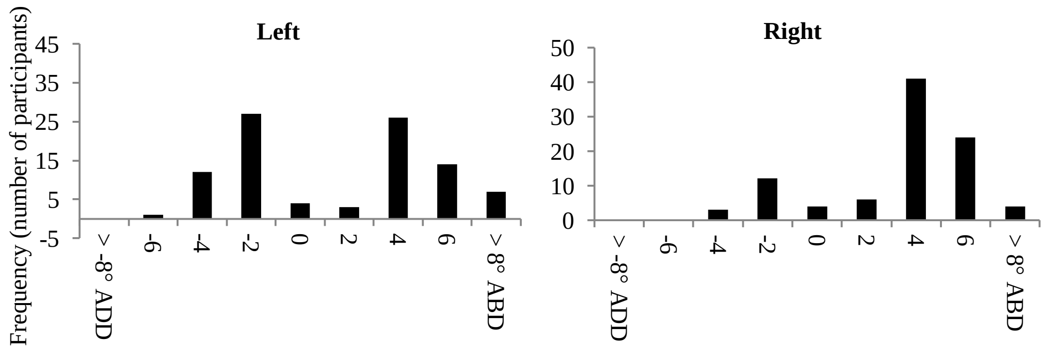


Figure 6.19e (left) and 6.19f (right): Histogram demonstrating the inter-participant variation in the range of transverse plane motion of the midfoot relative to the calcaneus during the swing phase. Positive range of motion: Abduction, Negative range of motion: Adduction.

Discussion

The main focus of Root et al (1977) description, and more recent investigations that have measured the function of the foot during gait is the the stance phase. Very few (Jenkyn and Nicol 2007, Simon et al 2006, Pierrynowski and Smith 1996) have described the movement of the foot during the swing phase. Therefore, it was deemed important for this investigation to present data describing the function of the foot during the swing phase.

Root et al (1977) proposed that during the swing phase the main function of the foot is to prepare for initial heel contact. They described how the subtalar joint will evert prior to toe off, and then it will supinate for the duration of the swing phase. This will in turn supinate the midtarsal joint around its longitudinal axis during the swing phase. However the results from this investigation, and others (Jenkyn and Nicol 2007, Simon et al 2006, Pierrynowski and Smith 1996) report that contrary to Root et al (1977) the calcaneus dorsiflexed, everted and abducted relative to the tibia during the swing phase. This indicates that instead the subtalar joint pronated during the swing phase. Simon et al (2006) reported only 4° eversion, while this investigation reports a greater range of eversion (left: -5.1° (SD = 7.8°), right: -7.9° (SD = 4.4°)). Although, the range of eversion in most feet is not enough to place the calcaneus in an everted position during the swing phase, or at initial heel contact. Therefore, the calcaneus remains in an inverted or supinated position, which is in part agreement with Root et al (1977).

In agreement with the Root et al hypothesis, this investigation and Jenkyn and Nicol (2007) report that the midfoot plantarflexed, inverted and abducted relative to the calcaneus during the swing phase. However, there is some inter-participant variation across all planes of motion. This indicates that there is an inconsistent pattern between feet in the direction of motion in the movement of the midfoot during the swing phase.

Overall, the results from this investigation are not in agreement with the Root et al (1977) description. This is because the calcaneus did not supinate relative to the tibia during the swing phase. Although the mean values indicate that the midfoot supinated relative to the calcaneus, the large inter-participant variation suggests that there is no definite movement pattern of the midfoot during the swing phase.

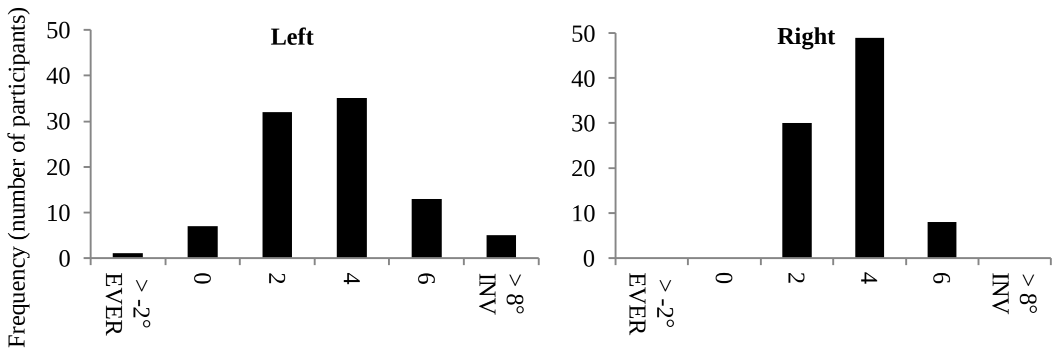
6.4.11 Root et al Hypothesis 11 - During the contact phase there is a greater range of kinematic motion evident in the forefoot, compared to the amount of motion evident during the phases of midstance and propulsion.

There is a greater or similar range of motion within the forefoot during the midstance and propulsion phases, than during the contact phase. Across all planes of motion there is a gradual increase in the range of motion of the lateral forefoot relative to the midfoot, and medial forefoot relative to the midfoot from the contact, to midstance and to propulsion phases. For example, on the left the range of sagittal plane motion of the lateral forefoot relative to the midfoot was only 2.2° (SD=2.7°) during contact phase. During midstance, this increased to 4.1° (SD=5.2°) and during propulsion to -11.6° (SD=4.7°) during propulsion. Although the range of frontal and transverse plane motion is smaller, there is a similar increase in the amount of motion.

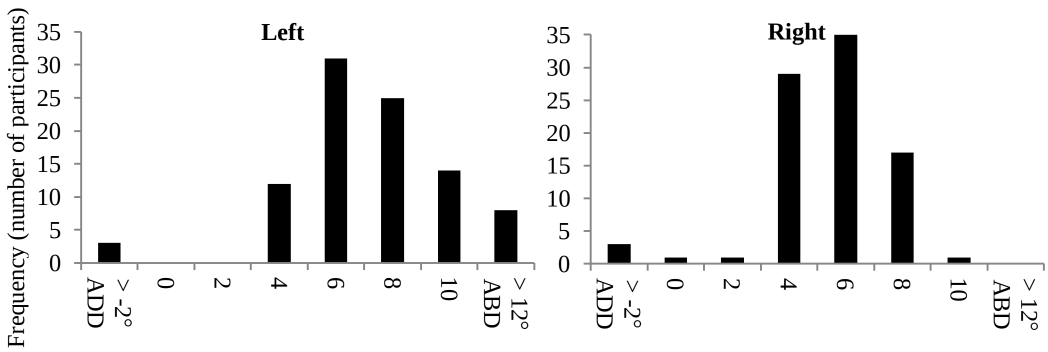
The standard deviation values are is most instances greater during midstance and propulsion. This indicates that there is greater inter-participant variation in the motion within these inter-segmental angles during these phases, than the contact phase. This is highlighted by the variation in Figures 6.20a-6.20f and 6.21a-6.21f which increase sequentially during the different stages of the gait cycle.

Plane of motion	Gait Parameter	Descriptive Analysis (+ve ROM DF/INV/ABD)	Lateral forefoot-Midfoot Left (n=93)	Lateral forefoot-Midfoot Right (n=87)	Medial forefoot-Midfoot Left (n=99)	Medial forefoot-Midfoot Right (n=90)
Sagittal (x)	ROM during contact phase	Mean (°)	2.2	1.9	0.8	-1.8
		SD (°)	2.7	1.8	2.7	2.5
		95% CI (°)	1.6- 2.7	1.5- 2.3	0.3- 1.3	-2.3- -1.2
	ROM during midstance	Mean (°)	4.1	3.3	5.9	5.8
		SD (°)	5.2	4.7	3.3	4.5
		95% CI (°)	3.0- 5.1	2.3- 4.3	5.2- 6.6	4.8- 6.7
	ROM during propulsion	Mean (°)	-11.6	-9.9	-13.5	-16.7
		SD (°)	4.7	4.5	5.1	7.8
		95% CI (°)	4.2- 7.4	-10.8- -8.9	-14.5- -12.5	-18.4- -15.1
Frontal (y)	ROM during contact phase	Mean (°)	-3.2	-1.9	-0.9	-0.2
		SD (°)	3.7	2.9	1.6	1.8
		95% CI (°)	-4.0- -2.5	-2.6- -1.3	-1.3- -0.7	-0.6- 0.2
	ROM during midstance	Mean (°)	-2.8	3.6	1.4	2.5
		SD (°)	9.6	6.4	3.7	3.5
		95% CI (°)	-4.8- -0.9	2.2- 4.9	0.6- 2.1	1.7- 3.2
	ROM during propulsion	Mean (°)	5.8	-4.9	-1.5	-2.7
		SD (°)	7.9	7.2	6.2	6.3
		95% CI (°)	4.2- 10.5	-6.5- -3.4	-2.7- -0.2	-4.0- -1.4
Transverse (z)	ROM during contact phase	Mean (°)	2.7	2.4	-0.3	-0.3
		SD (°)	2.8	1.0	1.1	1.2
		95% CI (°)	2.1- 3.2	2.2- 2.7	-0.5- -0.1	-0.6- -0.1
	ROM during midstance	Mean (°)	6.1	4.4	0.7	-0.9
		SD (°)	3.1	2.1	2.9	2.7
		95% CI (°)	5.5- 6.5	3.9- 4.9	0.1- 1.2	-1.5- -0.3
	ROM during propulsion	Mean (°)	-11.2	-8.2	-6.8	-1.3
		SD (°)	3.2	2.4	3.6	5.1
		95% CI (°)	-11.9- -10.5	-8.8- -7.7	-7.6- -6.1	-2.4- -0.2

Table 6.17 describes the mean range of sagittal, frontal and transverse plane motion of the lateral forefoot relative to the midfoot and the medial forefoot relative to the midfoot during the contact, midstance and propulsion phases. The number of feet displaying range of DF/PF, INV/EVER, ABD/ADD (n, %). The Max/Min range of DF/PF, INV/EVER, ABD/ADD (°).



Figures 6.20a (left) and 6.20b (right): Histogram demonstrating the inter-participant variation in the range of transverse plane motion of the lateral forefoot relative to the midfoot during the contact phase. Positive range of motion: Abduction, Negative range of motion: Adduction.



Figures 6.20c (left) and 6.20d (right): Histogram demonstrating the inter-participant variation in the range of transverse plane motion of the lateral forefoot relative to the midfoot during midstance. Positive range of motion: Abduction, Negative range of motion: Adduction.

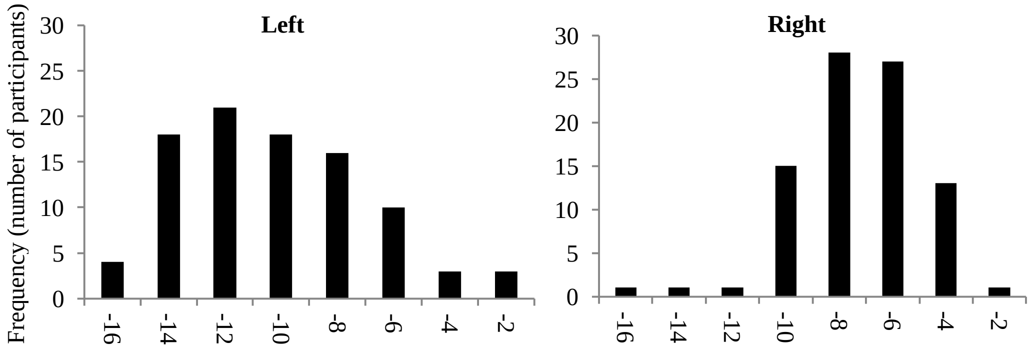


Figure 6.20e (left) and 6.20f (right) Histogram demonstrating the inter-participant variation in the range of transverse plane motion of the lateral forefoot relative to the midfoot during propulsion. Positive range of motion: Abduction, Negative range of motion: Adduction.

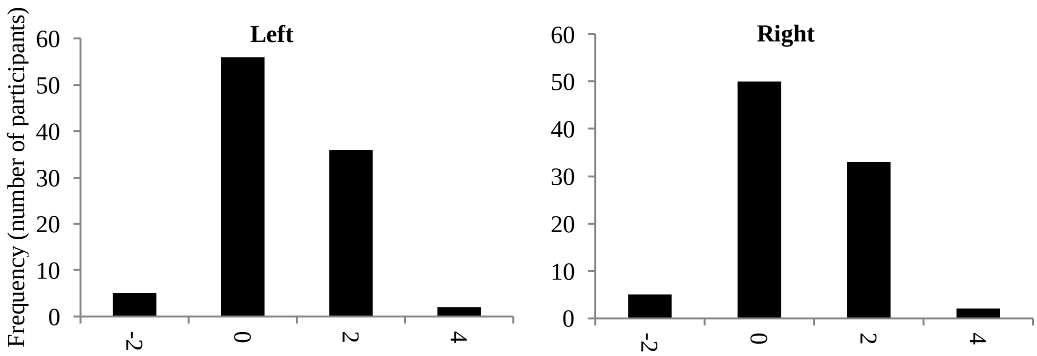


Figure 6.21a (left) and 6.21b (right): Histogram demonstrating the inter-participant variation in the range of transverse plane motion of the medial forefoot relative to the midfoot during the contact phase. Positive range of motion: Abduction, Negative range of motion: Adduction.

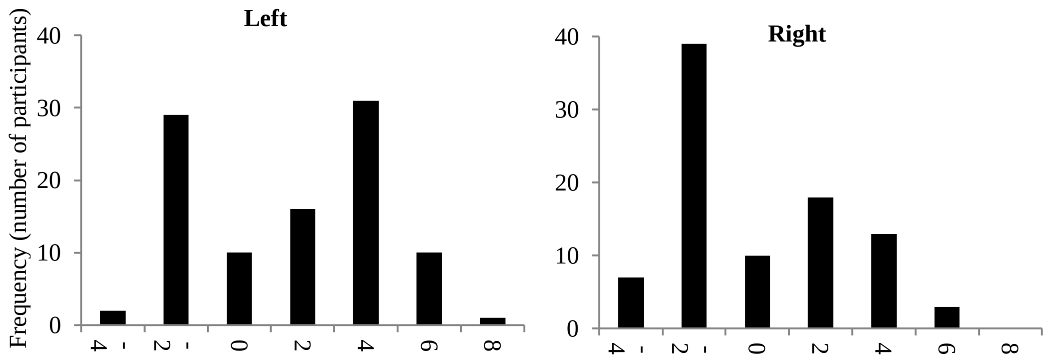


Figure 6.21c (left) and 6.21d (right): Histogram demonstrating the inter-participant variation in the range of transverse plane motion of the medial forefoot relative to the midfoot during midstance. Positive range of motion: Abduction, Negative range of motion: Adduction.

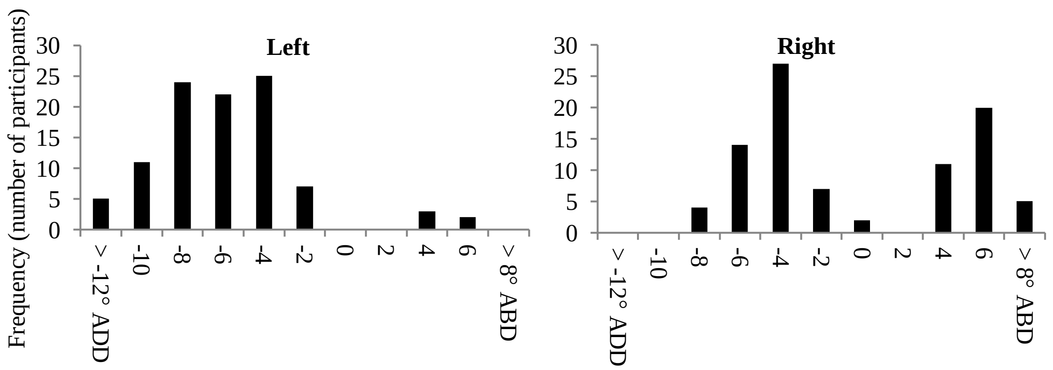


Figure 6.21e (left) and 6.21f (right): Histogram demonstrating the inter-participant variation in the range of transverse plane motion of the medial forefoot relative to the midfoot during propulsion. Positive range of motion: Abduction, Negative range of motion: Adduction.

Histogram data is only presented for the range of transverse plane motion of the lateral forefoot relative to the midfoot, and medial forefoot relative to the midfoot during the contact, midstance and propulsion phases. A similar pattern of motion was demonstrated by these inter-segmental angles during those phases of the gait cycle.

Discussion

Root et al (1977) proposed that the normal foot will function as a "mobile adaptor" during the contact phase, because there is skeletal flexibility within, and between the joints of the forefoot. During midstance and propulsion, they described how this normal foot will transform into a "rigid lever." This was proposed to create skeletal rigidity, and stability within the structure of the foot. The ability of the foot to function as a mobile adaptor or rigid lever is described by Root et al (1977) as a key determinant of what they propose is the normal function of the foot. Root et al (1977) would propose that if a foot cannot demonstrate either of these functions at those specific stages of the gait cycle, it is a cause of injury.

There are many difficulties with using the terms "mobile," or "rigid" to describe the anatomy, or function of the regions or joints of the human body. For example, describing a structure, or joint as rigid assumes there is no movement at all. The results of this investigation and others (Lundgren et al 2007, Hunt et al 2001a, DeMits et al 2012, Simon et al 2006, Nester et al 2006, Huson 1991, Vogler and Bojson-Moller 2000) have demonstrated that there is a greater range of motion within the forefoot during midstance and propulsion than there is during the contact phase. The joints within the foot do also not appear to be rigid or non-moving at any stages of the gait cycle. There is a sequential increase in the range of sagittal, frontal, and transverse plane motion between all inter-segmental angles within the foot, as it moves through the different stages of the gait cycle. This is especially evident within the forefoot. This indicates that the foot cannot be described to represent a mobile adaptor during the contact phase, and then a rigid lever during midstance and propulsion, if it is based on the range of motion within the foot.

Root et al (1977) would propose that there will be skeletal flexibility within the feet included in this, and these investigations (Lundgren et al 2007, Hunt et al 2001a, Simon et al 2006, Nester et al 2006, Cornwall and McPoil 1999a, Moseley et al 1996, Leardini et al 2007, Rattanaprasert et al 1999, Kitaoka et al 2006) and they will either be pre-disposed to, or present with injury. This is because as demonstrated by the results of Hypothesis 4 (Section 6.4.4) the calcaneus everted relative to the tibia or talus during midstance. Therefore, without supination of the subtalar joint Root et al (1977) proposed that the foot cannot transform into a rigid lever. However, all participants included in this, and other (Lundgren et al 2007, Hunt et al 2001a, Simon et al 2006, Nester et al 2006, Cornwall and McPoil 1999a, Moseley et al 1996, Leardini et al 2007, Kitaoka et al 2006, DeMits et al 2012) investigations are asymptomatic. This suggests that contrary to Root et al (1977), movement within the forefoot during midstance and propulsion is not necessarily a cause of abnormal or potentially pathological biomechanical movement. Instead, it strongly suggests that there needs to be movement within the foot during midstance and propulsion for normal function.

Root et al (1977) provided no description of the movement of the fifth ray during the gait cycle. The results from this investigation strongly indicate this region of the foot plays an important role in the aiding the function of the foot. For example, the range of frontal and transverse plane motion of the lateral forefoot relative to the midfoot is considerably greater than the medial forefoot relative to the midfoot. It can be hypothesised that is amount of movement within this region of the foot is important for terrain adaptation and stability of the foot. This suggests that in agreement with Huson (1991), the results from this investigation are indicative of a lateral arch of the foot, which is comparable or indeed more mobile than the medial arch. This highlights Root et al (1977) very poor description and understanding of the function of the forefoot during walking. It emphasises how the lack of literature available to Root et al (1977) has resulted in their description failing to adequately describe some of the very important functional units within the foot, such as the fifth ray.

A limitation of this investigation is that it has used skin mounted markers to measure the kinematic motion of the foot. Therefore, it is unable to describe the precise anatomical congruity of the foot or measure how the different bones move inter-dependently together. It is only possible to estimate through the measurement of the range of motion at an inter-segmental angle to indicate the flexibility, or rigidity within the foot.

A second limitation of how the medial arch of the foot, or the medial forefoot relative to the midfoot is measured in this investigation is that it does not incorporate the movement of the medial cuneiform. The small anatomical size of this bone makes it very difficult to detect its dimensions from the skin surface. Therefore it is only realistically possible to measure its movement via intra-cortical bone investigations. In those (Lundgren et al 2007, Nester et al 2006, Lundberg et al 1989a, Lundberg et al 1989b, Lundberg et al 1989c) that have measured its movement, they have reported a considerable range of motion between the medial cuneiform relative to the navicular. The range of motion is much less than between it and the first metatarsal. This may also indicate as to why the range of motion at what is defined as the medial and lateral arches of the foot (Huson 1991) would appear to be smaller on the medial side, than the lateral side of the foot.

Overall, the results from this investigation are not in agreement with the Root et al (1977) description. This is because the amount of motion measured within, and between the forefoot and midfoot, indicates that the foot does not resemble a mobile adaptor during the contact phase or a rigid lever during midstance and propulsion.

6.5 Results and Discussion – Research Question 2

The aim of this section is to demonstrate the results from this investigation, and present a discussion of these with the surrounding literature for each individual hypothesis within Research Question 2. This will aim to determine if the measurements, or classifications of a foot obtained from the Root et al (1971, 1977) static biomechanical assessment of the foot can predict the kinematics of the foot during the gait cycle.

6.5.1 Hypothesis 1 - NCSP will represent the position of the subtalar joint during midstance prior to heel lift in the normal foot

In 97% of feet on the left and right, the calcaneus was inverted relative to the tibia in NCSP. In NCSP, the calcaneus was inverted relative to the tibia a mean of 9.2° (SD=5.0°) on the left and, 9.0° (SD=5.1°) on the right (Figures 6.22a and 6.22b). This is not representative of the magnitude of the angle of the calcaneus in the frontal plane relative to the tibia at heel lift (left: -0.7° (SD = 4.0°), right: -0.7° (SD = 3.4°), or the peak angle of eversion during midstance (left: -3.9° (SD= 3.4°), right: -3.6° (SD= 3.2°)).

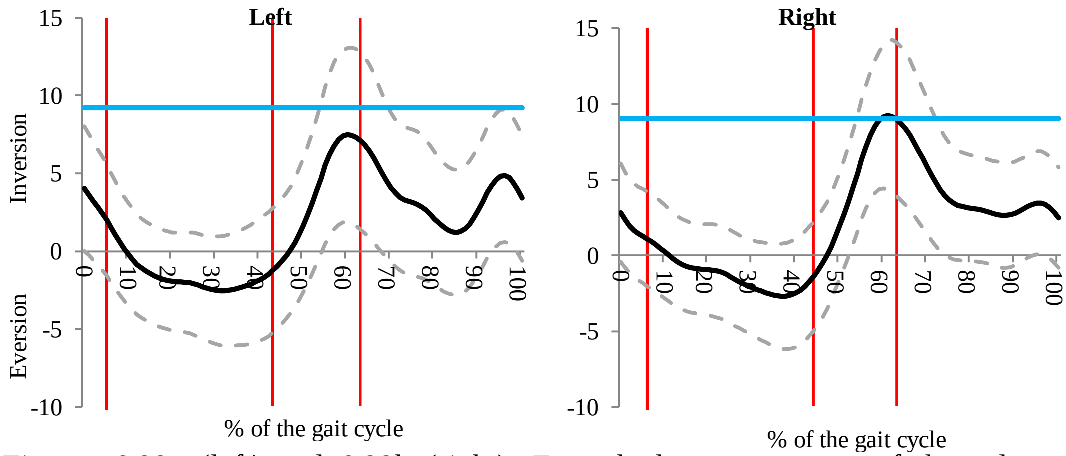
The frontal plane angle of the calcaneus relative to the tibia in NCSP is not correlated with the frontal plane angle of the calcaneus relative to the tibia at heel lift or at the peak angle of eversion during midstance (left: s = <0.352 (p<0.001), right: r = <0.194 (p=0.033) Table 6.19, Figures 6.22c-6.22f).

Segment	Descriptive Analysis (+ve angle INV)	Angle at NCSP* Left	Angle at NCSP* Right
Calcaneus-Tibia (Left n=90 Right n=91)	Mean (°)	9.2	9.0
	SD (°)	*5.0*	*5.1*
	95% CI (°)	8.2- 10.3	7.9- 10.1
	No. of feet INV angle (n, %)	*n=87 (97%)*	*n=88 (97%)*
	Max INV angle (°)	*19.5*	*29.1*
	Min INV angle (°)	*0.3*	*0.6*
	No. of feet EVER angle (n, %)	*n=3 (3%)*	*n=3 (3%)*
	Max EVER angle (°)	*-0.9*	*-2.9*
	Min EVER angle (°)	*-0.4*	*-0.1*

Table 6.18 describes the mean frontal plane angle of the calcaneus relative to the tibia in NCSP. The number of feet displaying angle of INV/EVER (n, %). The Max/Min angle of INV/EVER (°).* Measured relative to RCSP which is 0°.

Segment	Descriptive analysis (+ve angle INV)	Gait Parameter: Angle at heel lift Left	Angle at heel lift Right	Peak angle of EVER during midstance Left	Peak angle of EVER during midstance Right
Calcaneus-Tibia (Left n=90 Right n=91)	Mean (°)	-0.7	-0.7	-3.9	-3.6
	SD (°)	*4.0*	3.4	*3.4*	3.2
	95% CI (°)	*-1.5- 0.1*	-1.4- 0.03	*-4.6- -3.2*	-4.3- -2.9
	No. of feet INV angle (n, %)	*n=39 (43%)*	n=38 (42%)	*n=8 (9%)*	n=12 (13%)
	Max INV angle (°)	*8.5*	8.2	*5.4*	4.2
	Min INV angle (°)	*0.2*	0.1	*0.1*	0.04
	No. of feet EVER angle (n, %)	*n=51 (57%)*	n=53 (58%)	*n=82 (91%)*	n=79 (87%)
	Max EVER angle (°)	*-14.4*	-8.2	*-15.4*	-11
	Min EVER angle (°)	*-0.2*	-0.2	*-0.4*	-0.1
	Correlation r/s (p) with Angle at NCSP	s = 0.352 (<**0.001**)	r = 0.194 (**0.03**)	s = 0.313 (<**0.001**)	r = 0.154 (0.144)

Table 6.19 describes the mean frontal angle of the calcaneus relative to the tibia at heel lift and the peak angle of eversion during midstance. The number of feet displaying angle of INV/EVER (n, %). The Max/Min angle of INV/EVER (°). : Pearson's correlation. s: Spearman's correlation



Figures 6.22a (left) and 6.22b (right): Frontal plane movement of the calcaneus relative to the tibia during the gait cycle. Black solid line represents mean, and grey dashed lines represents standard deviation. Blue solid line represents mean frontal plane angle of the calcaneus relative to the tibia in NCSP.

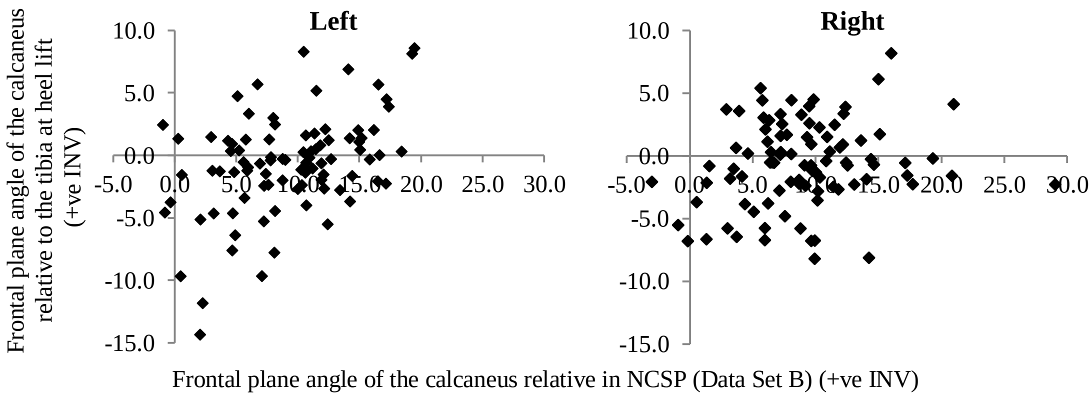
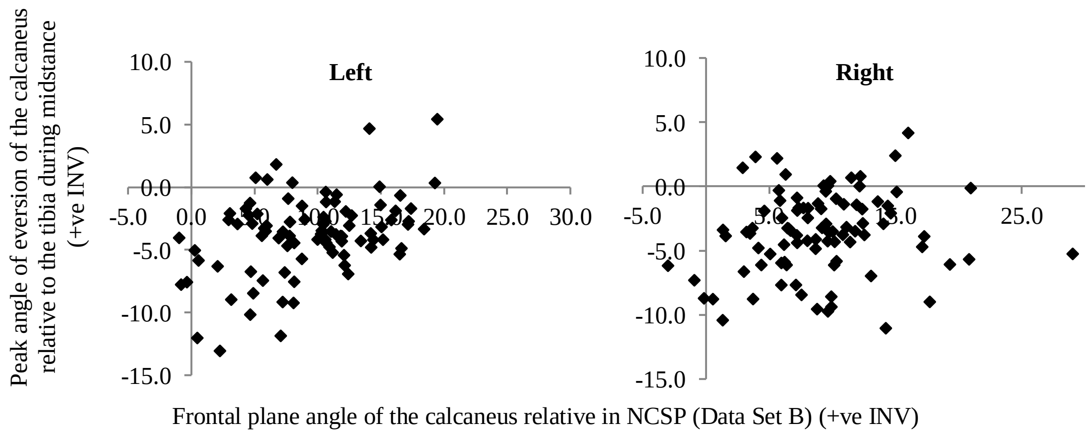


Figure 6.22c (left) and 6.22d (right) presents a scatter plot of the correlation between the frontal plane angle of the calcaneus relative to the tibia in NCSP and at heel lift



Figures 6.22e (left) and 6.22f (right) presents a scatter plot of the correlation between the frontal plane angle of the calcaneus relative to the tibia in NCSP and the peak angle of eversion during midstance.

Discussion

The examination of NCSP was proposed by Root et al (1971, 1977), and is described by podiatrists in Chapter 4, Section 4.2 as an important static examination of the foot. The measurement obtained from this examination would be used to predict the movement of the subtalar joint during the stance phase of walking, and for the manufacture of a foot orthoses device.

The calcaneus is not in a neutral position relative to the tibia when examined in NCSP, and nor is it everted during midstance the same magnitude of angle it is inverted in NCSP. This is in agreement with McPoil and Cornwall (1994) and McPoil and Cornwall (1996a). However, in this investigation the zero reference position used to measure any movement, or an angle between two segments was defined from RCSP. Therefore, any change in the position of the foot by placing the subtalar joint into a neutral position as it is in NCSP from RCSP would result in an inverted or everted angle. Although, Root et al (1977) hypothesised that in the normal foot the subtalar joint should be in a neutral position in RCSP, or within 2° everted to 2° inverted. However, the results from this investigation demonstrate that the inverted angle of the calcaneus relative to the tibia when placed in NCSP was much greater and in no foot was the calcaneus in a neutral (0°) angle relative to the tibia when placed in NCSP.

Some have reported a much smaller inverted angle of only 1.54° (SD = 3.6°) (McPoil and Cornwall 1994) and 1.2° (SD = 3.7°) (McPoil and Cornwall 1996a) for the placement of the subtalar joint into a neutral position when standing. However, both of these investigations use a different technique to Root et al (1971). Their method focused on placing the medial and lateral edges of the talus in congruence with the navicular. By asking the participant to lower or elevate their medial longitudinal arch the subtalar joint was proposed to be able to be placed into a neutral position. Therefore, the results do not represent the angle of the subtalar joint measured in NCSP as proposed by Root et al (1971).

For the examination of NCSP, all podiatrists in Chapter 4, Section 4.2 and investigations (Menz and Keenan 1997, Picciano et al 1993, Keenan and Bach 2006) only describe the measurement following the Root et al (1971) guidelines. Therefore, the results from McPoil and Cornwall (1994) and McPoil and Cornwall (1996a) do not represent what is being currently used in clinical practice.

Overall, either method of placing the placing the subtalar joint into a neutral position does not represent the position of the calcaneus relative to the tibia at heel lift, or during midstance. Therefore, suggesting that the neutral position of the subtalar joint is not a position used by the foot during the stance phase of walking. For example, in this investigation the calcaneus was everted relative to the tibia up to -3.9° (SD = 3.4°) on the left and -3.6° (SD = 3.2°) on the right during midstance. This is a much smaller magnitude than the angle measured in NCSP. The results from this investigation are similar to Leardini et al (2007) and others (Hunt et al 2001a, Cornwall and McPoil 1999a, Moseley et al 1996, Rattanaprasert et al 1999, Jenkyn and Nicol 2007, Kitaoka et al 2006). They reported that the calcaneus was everted relative to tibia between -1° to -3° at heel lift. Although conversely, McPoil and Cornwall (1994) and McPoil and Cornwall (1996a) report a greater everted angle at heel lift and during midstance than the results of this investigation. It is also greater than the inverted angle they measured in NCSP.

There are two key difficulties with the experimental protocol used by McPoil and Cornwall (1994) and McPoil and Cornwall (1996a). First, they placed two markers on bisection lines drawn onto the posterior aspect of the calcaneus, and another two overlaying the achilles tendon. Agreeably, this method is a good representation of the measurement techniques of Root et al (1971).However, Menz (1995) reported that a bisection line drawn onto the posterior aspect of the calcaneus does not truly bisect the frontal plane angle of it. Therefore, it questions whether the measurements recorded by McPoil and Cornwall (1994), McPoil and Cornwall (1996a) are an accurate representation of the frontal plane movement of the calcaneus or the subtalar joint. Second, the placement of markers onto the posterior aspect of the calcaneus and the achilles tendon would be highly subject to skin movement artefact. Therefore, it is reasonable to question the validity of the data obtained by these investigations.

In comparison, the methods used in this and other (Leardini et al 2007, Hunt et al 2001a, Cornwall and McPoil 1999a, Moseley et al 1996, Rattanaprasert et al 1999, Jenkyn and Nicol 2007, Kitaoka et al 2006) investigations are expected to offer a more valid representation of the frontal plane movement of the calcaneus relative to the tibia. This investigation and they (Hunt et al 2001a, Moseley et al 1996, Rattanaprasert et al 1999, Jenkyn and Nicol 2007, Kitaoka et al 2006, Nester et al 2007) have sought techniques to reduce skin movement artefact error. This includes carefully selecting areas to place retro-reflective markers that will be subject to less soft tissue movement, such as the medial and lateral aspects of the calcaneus.

Root et al (1977) proposed that if the subtalar joint is in a pronated or everted position at heel lift it is abnormal, and a cause of injury. However, all participants in this and other (Leardini et al 2007, Hunt et al 2001a, Cornwall and McPoil 1999a, Moseley et al 1996, Rattanaprasert et al 1999, Jenkyn and Nicol 2007, Kitaoka et al 2006, Lundgren et al 2007, Arndt et al 2004, McPoil and Cornwall 1994 and McPoil and Cornwall 1996a) investigations are asymptomatic. This questions Root et al (1977) description of what is proposed to represent the normal or abnormal foot. It also suggests that one of the key principles used in the manufacture of foot orthoses is incorrect. This is because the design of most functional foot orthoses is to ensure that during midstance the subtalar joint will be in a neutral position, and yet the asymptomatic foot remains in a pronated position at the subtalar joint. This suggests that a re-evaluation of the principles behind the mechanisms used when constructing orthoses for the control of rearfoot motion is required.

A limitation of this and other investigations (McPoil and Cornwall 1994, McPoil and Cornwall 1996) is that the position and movement of the calcaneus was measured relative to the tibia. Root et al (1977) only described the measurement and movement of the calcaneus in the frontal plane relative to the supporting surface. This is because the talus will according to Root et al (1971, 1977) move only in the sagittal and transverse planes when weight bearing.

Overall, this hypothesis is rejected. This is because the frontal plane angle of the calcaneus relative to the tibia measured in NCSP is not representative of the frontal plane angle of the calcaneus relative to the tibia during midstance, or at heel lift. The results from this hypothesis have also demonstrated that the frontal plane angle of the calcaneus relative to the tibia is not in a neutral angle in NCSP, and nor does it need to be for a foot to be symptom free.

6.5.2 Hypothesis 2.a - The range and angle of dorsiflexion that should be measured at the ankle joint in a static examination, and during midstance in the normal foot is 10°. Feet that do not demonstrate 10° of dorsiflexion at the ankle joint in a static examination, will not dorsiflex to 10° at the ankle joint during midstance.

Most feet were classified with less than 10° (left: 84%, right: 84%) range of dorsiflexion at the ankle joint from static examination, than more than 10° (left: 16%, right: 16%). In the majority of feet classified with <10°, >10°, <15°,or >15° range of dorsiflexion at the ankle joint from a static examination, the calcaneus is not dorsiflexed more than 10° relative to the tibia at heel lift (right: <10° classification = 5.4° (SD = 5.4°), >10° classification = 6.6° (SD = 3.1°). Similarly, the peak angle of dorsiflexion is less than 10° during midstance (right: <10° classification = 5.4° (SD = 4.4°), >10° classification = 6.7° (SD = 3.1°)) (Table 6.21, Figures 6.23a and 6.23b). In 9/98 feet on the left, and 7/99 feet on the right were dorsiflexed more than 10° for both, or either of these gait parameters.

Between feet classified with >10°, or <10° from a static examination the difference in the sagittal plane angle of the calcaneus relative to the tibia at heel lift, or the peak angle of dorsiflexion during midstance is <1.0° (SEM=1.1), (p = 0.184) on the left, and <1.3° (SEM=1.1), (p = 0.139) on the right. Figures 6.23a and 6.23b emphasise how there is no difference in sagittal plane movement of the calcaneus relative to the tibia throughout the gait cycle in feet classified with <10° or >10°. The difference between feet classified with <10° or >15° at heel lift, or the peak angle of dorsiflexion during midstance was not more than 0.4° (SEM = 1.7), (p = 0.417) (right only).

Descriptive analysis (+ve angle DF)	Left		Right		Left		Right	
	<10°	>10°	<10°	>10°	<15°	>15°	<15°	>15°
Number of feet (n)	n=83	n=15	*n=83*	n=16	n=#	n=#	n=92	n=7
Mean (°)	4.8	11.9	3.5	14.6			4.2	17.1
SD (°)	*2.8*	*1.8*	*3.0*	*3.4*			*3.6*	*1.7*
95% CI (°)	*4.2- 5.4*	*10.9- 12.9*	*2.8- 4.1*	*13.2- 16.1*			*3.4- 4.4*	*15.6- 18.7*
No. of feet DF angle (n, %)	*n= 81 (97%)*	*n=15 (100%)*	*n=80 (96%)*	*n=16 (100%)*			*n=89 (97%)*	*n=7 (100%)*
Max DF angle(°)	*9.0*	*15.0*	*9.0*	*19.0*			*12.0*	*19.0*
Min DF angle (°)	*1.0*	*10.0*	*1.0*	*10.0*			*0.0*	*15.0*

Table 6.20 describes the mean range of dorsiflexion at the ankle joint measured from a static examination (Data Set A). All feet were classified as <10° or >10° and <15° or >15° range of dorsiflexion at the ankle joint. #: Indicates in-sufficient numbers of feet for >15° group (n=1). The number of feet displaying range of DF (n, %). The Max/Min range of DF (°).

Segment	Gait Parameter	Descriptive Analysis (+ve angle DF)	Left		Right		Left		Right	
			<10°	>10°	<10°	>10°	<15°	>15°	<15°	>15°
Calcaneus-Tibia		Number of feet (n)	n=83	n=15	*n=83*	*n=16*	#	#	*n=92*	*n=7*
	Angle at heel lift	Mean (°)	5.5	6.5	5.4	6.6			5.6	5.7
		SD (°)	*4.0*	*3.6*	*4.5*	*3.1*			*4.4*	*3.1*
		95% CI (°)	*4.6- 6.4*	*4.5- 8.5*	*4.4- 6.3*	*4.9- 8.2*			*4.7- 6.5*	*2.9- 8.5*
		No. of feet DF angle (n, %)	*n=76 (92%)*	*n=14 (93%)*	*n=76 (92%)*	*n=15 (94%)*			*n=85 (92%)*	*n=6 (86%)*
		Max DF angle(°)	*21.3*	*11.9*	*19.5*	*13.8*			*19.5*	*8.7*
		Min DF angle (°)	*0.1*	*0.6*	*0.8*	*4.6*			*0.5*	*5.0*
		Comparison p	0.184		0.147				0.467	
	Peak angle of DF during midstance	Mean (°)	5.6	6.6	5.4	6.7			5.6	5.8
		SD (°)	*3.9*	*3.6*	*4.4*	*3.1*			*4.3*	*3.1*
		95% CI (°)	*4.8- 6.5*	*4.6- 8.6*	*4.5- 6.4*	*5.0- 8.3*			*4.7- 6.5*	*2.9- 8.7*
		No. of feet DF angle (n, %)	*n=76 (92%)*	*n=14 (93%)*	*n=76 (92%)*	*n=15 (94%)*			*n=86 (93%)*	*n=6 (86%)*
		Max DF angle(°)	*21.3*	*12.1*	*19.5*	*13.8*			*19.5*	*8.8*
		Min DF angle (°)	*0.5*	*0.9*	*0.6*	*4.6*			*0.6*	*5.0*
		Comparison p	0.195		0.139				0.461	

Table 6.21 describes the mean sagittal plane angle of the calcaneus relative to the tibia at heel lift and the peak angle of dorsiflexion during midstance in feet classified with <10°, >10°, <15° and >15° range of dorsiflexion measured from static examination (Table 6.20) with comparison (p) between classifications of feet. The number of feet displaying angle of DF (n, %). The Max/Min range or angle of DF (°). #Indicates in-sufficient numbers of feet for >15° group (n=1).

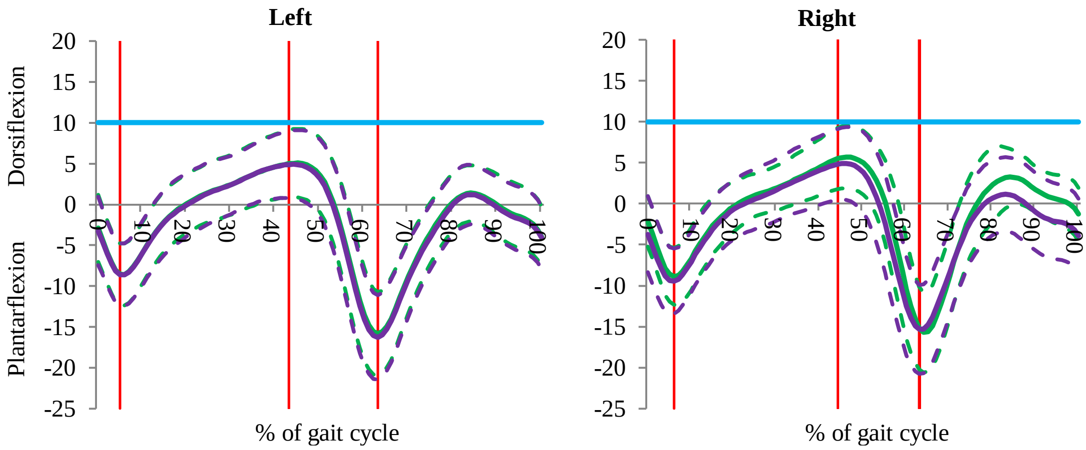
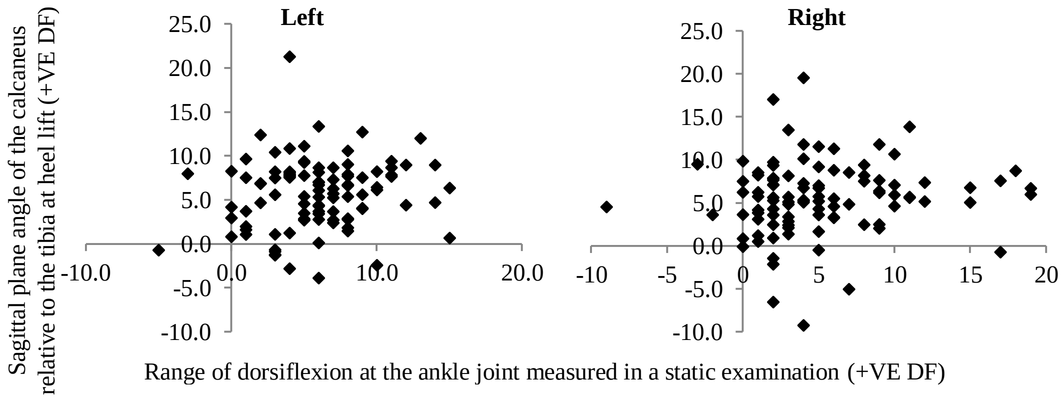


Figure 6.23a (left) and 6.23b (right): Sagittal plane movement of the calcaneus relative to the tibia during the gait cycle. Purple line : <10°. Green line:>10°. Blue line: represents 10° of dorsiflexion (Root et al (1977). Solid line represents mean value, and dashed line represents standard deviation. Red vertical lines represent the timing of forefoot loading, heel lift and toe off.

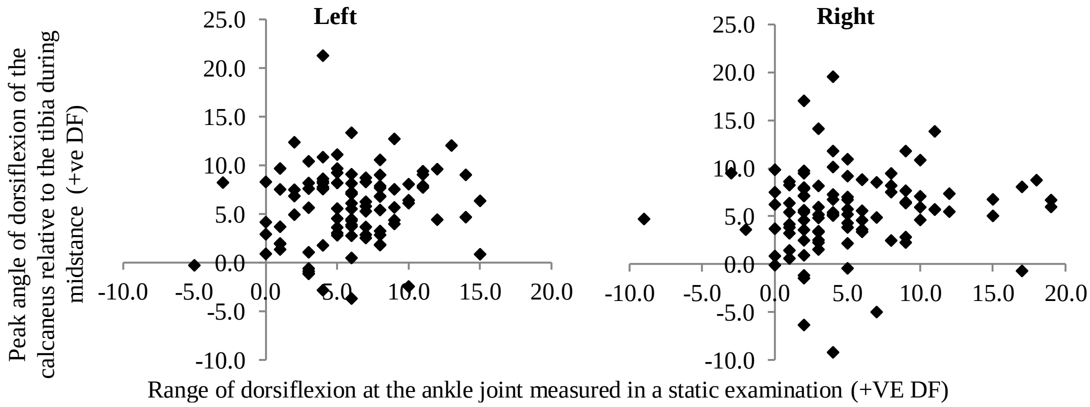
All s values indicate low correlation (s (p)) between the range of dorsiflexion at the ankle joint measured in static examination and both gait parameters (left: s = <0.139 (p = 0.09), right s = <0.162 (p = 0.06)) (Table 6.22 and Figures 6.23c-6.23f).

Static Examination	Gait Parameter for Calcaneus-Tibia	Correlation s (p)	
		Left (n=98)	Right (n=99)
Range of dorsiflexion at the ankle joint measured from static examination (Data set A)	Angle at heel lift	0.139 (0.09)	0.156(0.06)
	Peak angle of DF during midstance	0.137 (0.09)	0.162 (0.06)

Table 6.22 presents the results of correlations (s (p)) between the range of dorsiflexion at the ankle joint measured in static examination, and the sagittal angle of the calcaneus relative to the tibia at heel lift and the peak angle of dorsiflexion during midstance. s: spearman correlation



Figures 6.23c (left) and 6.23d (right) presents a scatter plot of the correlation between the range of dorsiflexion measured at the ankle joint in a static examination and the sagittal plane angle of the calcaneus relative to the tibia at heel lift.



Figures 6.23e (left) and 6.23f (right) presents a scatter plot of the correlation between the range of dorsiflexion measured at the ankle joint in a static examination and the peak angle of dorsiflexion of the calcaneus relative to the tibia during midstance.

Discussion

The examination of the range of dorsiflexion at the ankle joint was proposed by Root et al (1971 and 1977), and is described by podiatrists in Chapter 4, Section 4.2 as an important static examination of the foot. Podiatrists stated that the measurements obtained from this examination would be used to predict the movement of the ankle, and subtalar joints during the stance phase of walking. However, the results presented in this investigation question the reliability, validity, and therefore the clinical use of the static examination of the range of dorsiflexion at the ankle joint.

The results presented in Chapter 4 of this investigation indicate that the static examination of the ankle joint is not reliable. There was only moderate agreement between assessors. The large inter-assessor variation in the measurements obtained indicates that precise and reliable measurements are not possible with this examination technique. This is in agreement with Elveru et al (1988), Jonson and Gross (1997) and Moseley and Adams (1991).

Root et al (1977) stated that for a foot to be classified as normal, the range of dorsiflexion to be measured in a static examination of the ankle joint must be 10°. They proposed that this will indicate whether the ankle joint will be able to dorsiflex to 10° at heel lift. However, this investigation presents a significant amount of evidence to question these key determinants of the normal foot. First, in the majority of asymptomatic participants the range of dorsiflexion measured in a static examination is much less than 10°. Second, in agreement with others (Moseley et al 1996, Leardini et al 2007, Lundgren et al 2007, Arndt et al 2004, Kitaoka et al 2006, and Cornwall and McPoi1 1999a), this investigation reports that the calcaneus is not dorsiflexed to 10° relative to the tibia, but instead to between 5-7°. Third, there was no significant difference in the sagittal plane angle of the calcaneus relative to the tibia in feet classified will less than, or more than 10° of dorsiflexion from static examination. Even in feet classified with more than 10° the calcaneus was dorsiflexed to much less than 10° during midstance and at heel lift. This indicates that most feet do not need to dorsiflex at the ankle joint to 10° at heel lift to be symptom free. It suggests that contrary to Root et al (1977), 10° of dorsiflexion should not be used as a classification parameter for determining the normal or abnormal foot.

The poor correlation results between the static examination of the range of dorsiflexion at the ankle joint, and the movement of the calcaneus relative to the tibia emphasises the lack of a relationship between these parameters. Cornwall and McPoil (1999b) reported similar correlation values to this investigation with r = 0.116. However, some of their results could be construed to be in part agreement with Root et al (1977). They stated that in feet classified with less than 10° of dorsiflexion from the static examination of the ankle joint, the timing of heel lift was significantly earlier than feet classified with more than 15°. An early heel lift was described by Root et al (1977) as a key indicator of a limitation in the range of sagittal plane motion at the ankle joint. However all participants included in Cornwall and McPoil (1999) are asymptomatic, and the large standard deviation values (<10.2) indicate that there is large inter-participant variation in the timing of heel lift.

Orendurff et al (2006) suggested that the static examination of the ankle joint could be used to infer possible differences in foot pressure. In patients diagnosed with diabetes, Orendurff et al (2006) reported that the plantar pressure under the forefoot was significantly greater in feet classified with less than 5° of dorsiflexion from the static examination of the ankle joint, than those classified with more than 5°. As all participants in Orendurff et al (2006) were diagnosed with diabetes, it is probable that in agreement with Turner et al (2006) other structural and neurological changes causing an increased stiffness in the soft tissues within the foot will have occurred. These may have caused the changes in foot pressure, rather than solely the range of motion at the ankle joint.

A limitation of this investigation, is that using the movement of the calcaneus in the sagittal plane relative to the tibia does not measure the exact movement of the ankle joint. However, the results from this investigation and others (Moseley et al 1996, Leardini et al 2007, Kitaoka et al 2006, Hunt et al 2001a, Cornwall and McPoil 1999a, Nester et al 2007) are comparable to those using intra-cortical bone pins (Lundgren et al (2007), Siegler et al (1988), Nester et al (2006), and Arndt et al (2004)). The measurement of the calcaneus relative to the tibia appears to provide a good representation of the angle, and range of sagittal plane motion at the ankle joint during the midstance phase of walking. Therefore the results presented here should have a valuable clinical output.

A key feature of the method of examination of the range of dorsiflexion at the ankle joint used in this investigation is that the subtalar joint was positioned in a neutral position prior to the movement of the foot. This is stipulated by Root et al (1971, 1977) as essential. Failure to do so is proposed by them to increase the range of dorsiflexion measured. Therefore it is not an accurate representation of its true range of dorsiflexion available. Most investigations (Elveru et al 1988, Diamond et al 1989, Jonson and Gross 1997, Menz et al 2003, Cornwall and McPoil 1999b) have failed to include this stage of the examination. This suggests that the results of this investigation are more pertinent than others, because they follow explicitly Root et al (1971, 1977) instructions.

Overall, hypothesis 2.a is rejected. This is because the static examination of the range of dorsiflexion at the ankle joint is unable to predict the sagittal plane angle of the calcaneus relative to the tibia during midstance. The results from this investigation also demonstrate that to be symptom free the ankle joint does not have to dorsiflex to 10° during midstance.

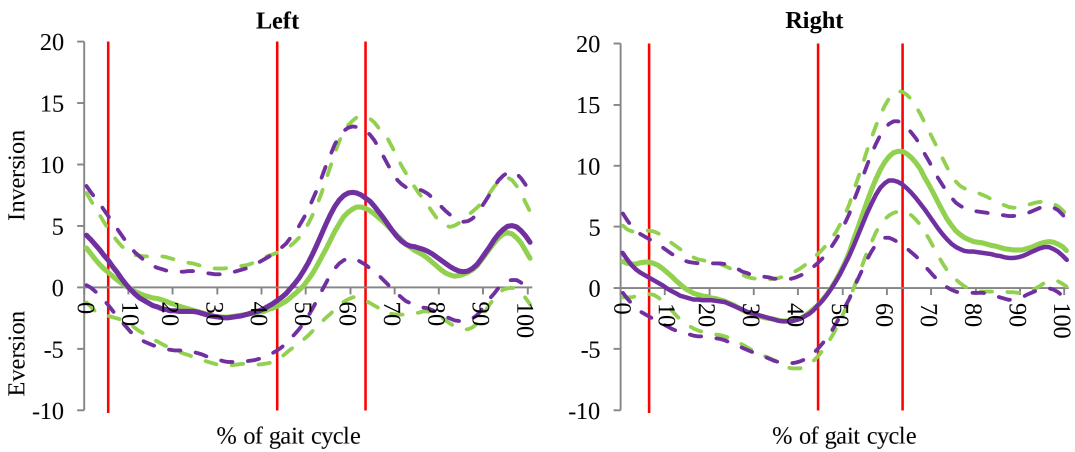
6.5.3 Hypothesis 2.b - Feet that cannot demonstrate 10° of dorsiflexion in the static examination of the ankle joint, will pronate at the subtalar joint during midstance

In agreement with the hypothesis, in the majority of feet classified with <10° of dorsiflexion at the ankle joint from static examination, the calcaneus everted relative to the tibia during midstance (left: -4.6° (SD=5.3°)), and is in an everted position at heel lift (left: -0.8° (SD=3.9°)) (Table 6.23). However, the calcaneus everted relative to the tibia in the majority of feet classified with >10° and >15° of dorsiflexion at the ankle joint from static examination.

Across all gait parameters tested the movement and angle of the calcaneus in the frontal plane relative to the tibia, and the timing of this movement was similar in feet classified with <10° or >10°, which is also demonstrated by Figure 6.24a and 6.24b. In feet classified with <10° the calcaneus was more everted relative to the tibia at heel lift only -0.2° (SD = 1.1°), p = 0.486) on the left, and -0.6° (SEM =1.0°), (p= 0.356) on the right than feet classified with >10°.

Segment	Plane of motion	Gait Parameter #	Descriptive Analysis (+ve angle/ROM INV)	Left		Right		Left		Right	
				<10°	>10°	<10°	>10°	<15°	>15°	<15°	>15°
Calcaneus - Tibia	Frontal (y)	Number of feet (n)		n=83	n=15	n=83	n=16	#	#	n=92	n=7
		Angle at heel lift	Mean (°)	-0.8	-0.9	-1.0	-0.4			-0.9	-1.5
			SD (°)	*3.9*	*4.3*	*3.5*	*3.9*			*3.5*	*4.6*
			95% CI (°)	*-1.7- 0.2*	*-3.3- 1.4*	*-1.8- -0.2*	*-2.5- 1.6*			*-1.6- -0.2*	*-5.8- 2.8*
			Comparison p	0.486		0.356				0.333	
		Peak angle of EVER during midstance	Mean (°)	-3.9	-4.1	-3.8	-3.8			-3.8	-4.0
			SD (°)	*3.3*	*3.8*	*3.3*	*3.5*			*3.2*	*4.6*
			95% CI (°)	*-4.7- -3.3*	*-6.2- -1.9*	*-4.5- -3.0*	*-5.7- -1.9*			*-4.2- -3.1*	*-8.3- -0.2*
			Comparison p	0.363		0.477				0.424	
		Time to peak angle of EVER during midstance **	Mean (% of gait cycle)	28.5	30.5	32.4	31.7			32.2	33.9
			SD (%)	*7.4*	*9.9*	*7.3*	*8.5*			*7.5*	*7.3*
			95% CI (%)	*26.9- 30.1*	*25.0- 35.9*	*30.9- 34.0*	*27.2- 36.2*			*30.7- 33.8*	*27.2- 40.8*
			Comparison p	0.08		0.436				0.229	

Table 6.23 describes the mean angle and range of frontal plane motion of the calcaneus relative to the tibia at heel lift during midstance in feet classified with <10°, >10°, <15° and >15° range of dorsiflexion measured from static examination (Table 6.21) with comparison (p) between classifications of feet. #Indicates in-sufficient numbers of feet for >15° group (n=1).

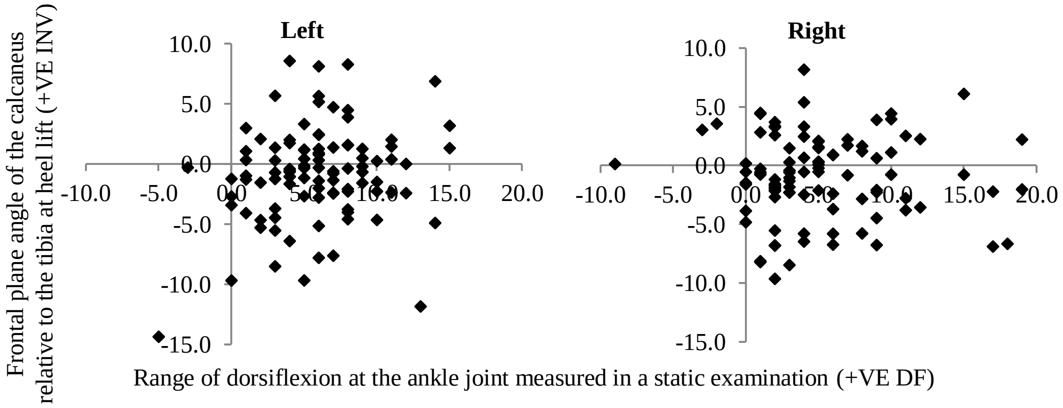


Figures 6.24a (left) and 6.24b (right): Frontal plane movement of the calcaneus relative to the tibia during the gait cycle. Purple line represents feet classified with <10°. Green line represents feet classified with >10°. Solid line represents mean value, and dashed line represents standard deviation. Red vertical lines represent the timing of forefoot loading, heel lift and toe off.

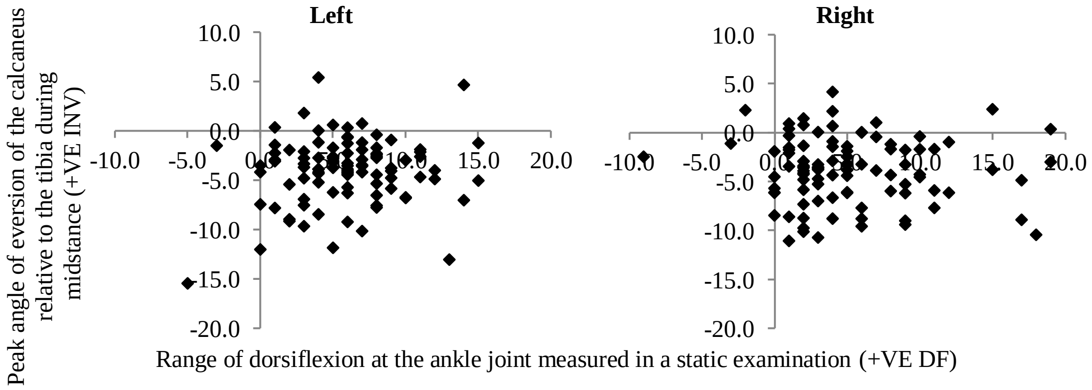
All r values indicate no to low correlation between the range of dorsiflexion at the ankle joint measured in static examination and the angle and timing of frontal plane movement of the calcaneus relative to the tibia (left: s =<0.151 (p = 0.07), right: s = <-0.213 (p = 0.02)) (Table 6.23 and Figures 6.24c-6,24h).

Static Examination	Gait Parameter for Calcaneus-Tibia	Correlation r/s (p)	
		Left (n=98)	Right (n=99)
Range of dorsiflexion at the ankle joint measured from static examination (Data set A)	Angle at heel lift	s = 0.151 (0.07)	r = -0.017 (0.866)
	Peak angle of EVER during midstance	s = 0.05 (0.324)	r = -0.06 (0.567)
	Time to peak angle of EVER during midstance	r = -0.04 (0.703)	s = 0.108 (0.143)

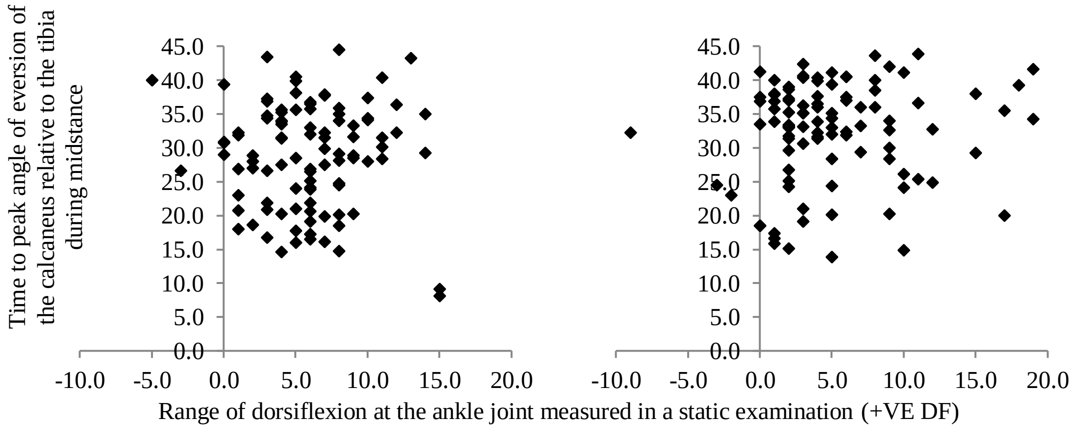
Table 6.24 presents the results of correlation (r/s (p)) between the range of dorsiflexion measured from a static examination (Data set A), and the angle of the calcaneus in the frontal plane relative to the tibia at heel lift, the peak angle of eversion and the time to reach this peak angle of eversion. r: Pearson correlation. s: Spearman correlation



Figures 6.24c (left) and 6.24d (right) presents a scatter plot of the correlation between the range of dorsiflexion measured at the ankle joint in a static examination and the frontal plane angle of the calcaneus relative to the tibia at heel lift.



Figures 6.24e (left) and 6.24f (right) presents a scatter plot of the correlation between the range of dorsiflexion measured at the ankle joint in a static examination and the peak angle of eversion of the calcaneus relative to the tibia during midstance.



Figures 6.24g (left) and 6.24h (right) presents a scatter plot of the correlation between the range of dorsiflexion measured at the ankle joint in a static examination and the time to peak angle of eversion of the calcaneus relative to the tibia during midstance.

Discussion

Root et al (1977) proposed that to compensate for a limited range of dorsiflexion at the ankle joint, the subtalar joint would pronate during midstance. This was described by them to create skeletal flexibility within the foot, which would ensure that it could remain in plantigrade contact with the supporting surface. Root et al (1977) also proposed that this increased flexibility within the foot is a cause of injury, as it will place abnormal stresses on the foot and leg.. However, the results from this investigation demonstrate as similar to many (Leardini et al 2007, Rattanaprasert et al 1999, Jenkyn and Nicol 2007, Kitaoka et al 2006, Cornwall and McPoil 1999a, Cornwall and McPoil 1999, Hunt et al 2001a, Lundgren et al 2007) that the calcaneus everted relative to the tibia or talus during midstance. All participants included in these investigations are asymptomatic. This suggests that contrary to Root et al (1977) pronation of the subtalar joint during midstance is not a cause of injury.

In agreement with Cornwall and McPoil (1999b), the results from this investigation also demonstrate that the range of dorsiflexion at the ankle joint measured from static examination cannot infer the frontal plane movement of the calcaneus relative to the tibia during midstance. The correlation values reported by both investigations indicate a lack of a relationship between these parameters. For example, this investigation reports $s = <0.151$ ($p = 0.07$), and Cornwall and McPoil (1999b) reported $r = 0.241$ ($p = 0.05$). This investigation and Cornwall and McPoil (1999b) describe no statistical significant difference in the frontal plane movement of the calcaneus relative to the tibia in feet classified with <10°, >10°, or >15° A limitation of this investigation is that using the angle, or range of frontal plane motion of the calcaneus relative to the tibia does not measure the exact movement of the subtalar joint. However, the results from this investigation and others (Moseley et al 1996, Leardini et al 2007, Kitaoka et al 2006, Hunt et al 2001a, Cornwall and McPoil 1999a, Nester et al 2007) indicate that they are comparable to the results from those that have used intra-cortical bone pin (Lundgren et al 2007, Siegler et al 1988, Nester et al 2006, and Arndt et al 2004). The method chosen to measure the movement of the subtalar joint during walking in this investigation is similar to Root et al (1977) description of the movement of the subtalar joint. They state that only the calcaneus will move in the frontal plane relative to the supporting surface. This is because the talus will according to Root et al (1971, 1977) move only in the sagittal and transverse planes when weight bearing.

Overall, hypothesis 2.b is rejected. This is because the static examination of the range of dorsiflexion at the ankle joint is unable to predict the angle, or range of frontal plane motion of the calcaneus relative to the tibia during midstance.

6.5.4 Hypothesis 3 - A foot which is classified with a rearfoot varus deformity defined from static examination will pronate and remain in a pronated position at the subtalar joint during midstance. This is compared to a normal foot which will supinate during midstance.

All feet examined from this cohort were classified as a rearfoot varus, with the exception of 1/99 on the left and 1/100 on the right (Table 6.24).

In agreement with the hypothesis the calcaneus everted relative to the tibia during midstance in the majority of feet classified with a rearfoot varus with 81% of feet (mean = -4.5° (SD=5.3°)) on the left, and 82% of feet (mean= -4.4° (SD= 4.4°)) on the right (Table 6.25, Figures 6.25a-6.25b). At heel lift, the calcaneus was everted relative to the tibia at heel lift in some (left: 59%, right: 59%) of the feet classified with a rearfoot varus. Although the calcaneus was -3.1° (SEM = 0.2), $p = <0.001$ on the left, and -2.9° (SEM = 0.2), $p = <0.001$ on the right more everted at the peak angle of eversion during midstance, than the angle at heel lift. This indicates that contrary to the hypothesis the majority of feet have inverted during the latter stages of midstance.

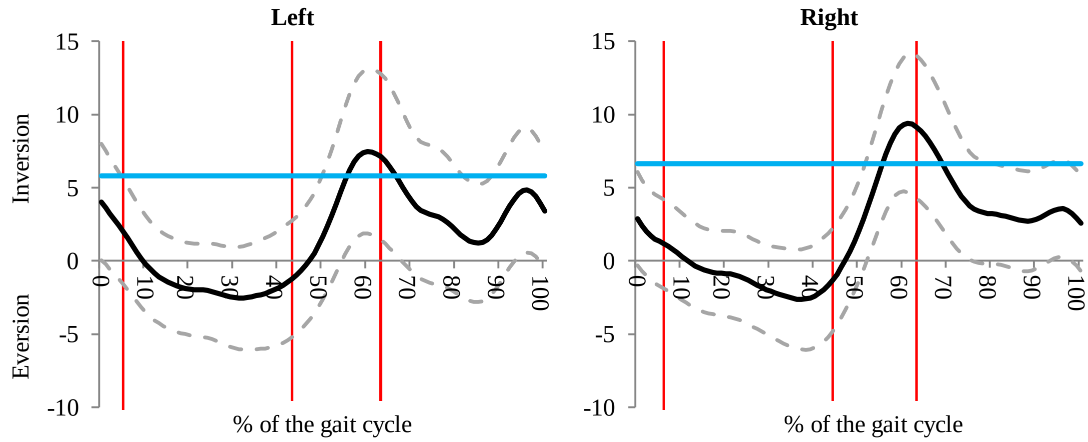
There was no relationship between the frontal plane angle of the calcaneus relative to the supporting surface measured in NCSP, and the frontal plane angle or range of motion of the calcaneus relative to the tibia during midstance (left: $s = < -0.158$ ($p = 0.06$), right: $s = <0.200$ ($p = 0.02$)) (Table 6.26, Figures 6.25c-6.25h).

Descriptive Analysis (+ve angle INV)	Angle at NCSP	
	Left	Right
No. of feet (n)	n=98	*n=99*
Mean (°)	5.8	6.6
SD (°)	*2.7*	*2.9*
95% CI (°)	*5.3- 6.4*	*6.0- 7.1*
Max INV angle (°)	*13.0*	*14.0*
Min INV angle (°)	*1.0*	*1.0*

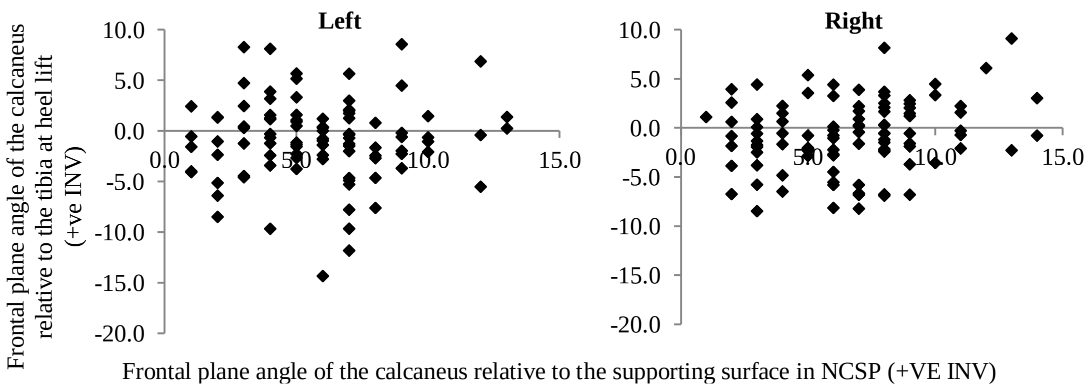
Table 6.25 describes the mean frontal angle of the calcaneus relative to supporting surface in NCSP in feet classified with a rearfoot varus from static examination (Data set A). The Max/Min angle of INV/EVER(°).

Segment	Plane of motion	Descriptive analysis (+ve angle and ROM INV)	Gait Parameter					
			Angle at heel lift		Peak EVER angle during midstance		ROM during midstance	
			Left	Right	Left	Right	Left	Right
Calcaneus-Tibia (Left n=98 Right n=99)	Frontal (y)	Mean (°)	-0.9	-0.7	-3.9	-3.6	-4.5	-4.4
		SD (°)	*3.9*	*3.6*	*4.3*	*3.3*	*5.3*	*4.4*
		95% CI (°)	*-1.6- -0.6*	*-1.4- -0.01*	*-3.4- -1.7*	*-4.3- -3.0*	*-5.6- -3.5*	*-5.3- -3.5*
		No. of feet INV angle/ROM (n, %)	*n=40 (41%)*	*n=41 (41%)*	*n=8 (8%)*	*n=14 (14%)*	*n=17 (17%)*	*n=18 (18%)*
		Max INV angle/ROM (°)	*8.5*	*9.1*	*5.4*	*4.2*	*10.6*	*6.1*
		Min INV angle/ROM (°)	*0.2*	*0.1*	*0.1*	*0.04*	*2.9*	*1.8*
		No. of feet EVER angle/ROM (n,%)	*n=58 (59%)*	*n=58 (59%)*	*n=90 (92%)*	*n=85 (86%)*	*n=81 (83%)*	*n=81 (82%)*
		Max EVER angle/ROM (°)	*-14.3*	*-8.5*	*15.4*	*-11.0*	*-16.5*	*-12.9*
		Min EVER angle/ROM (°)	*-0.2*	*-0.2*	*-0.4*	*-0.4*	*-2.2*	*-2.8*
		Correlation r/s (p) Angle at NCSP (Data Set A) and Gait Parameter	s = -0.158 (0.06)	s = 0.200 (**0.02**)	s = 0.02 (0.406)	r = 0.201 (**0.05**)	s = -0.01 (0.459)	r = -0.147 (0.148)

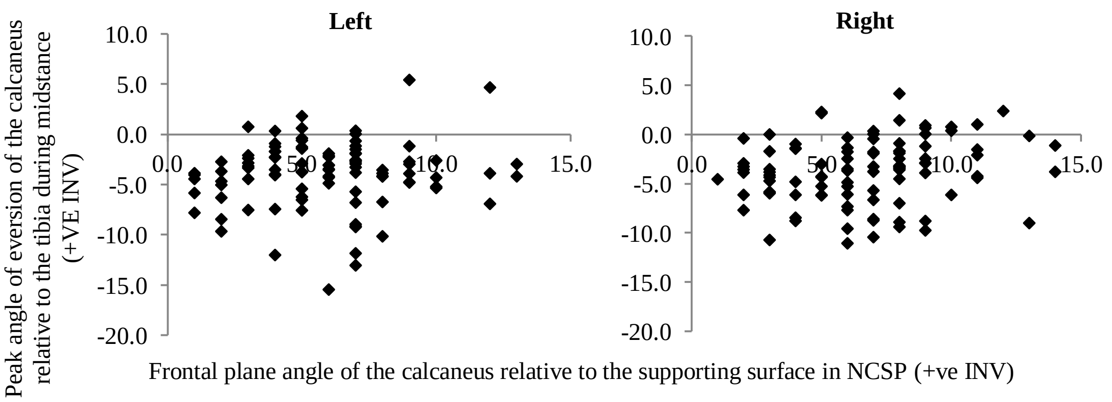
Table 6.26 describes the mean frontal plane angle and range of motion of the calcaneus relative to the tibia during midstance and at heel lift in feet classified with a rearfoot varus with correlation (r/s (p)) between these gait parameters and the results from Table 6.25. The number of feet displaying range or angle of INV/EVER (n, %). The Max/Min range or angle of INV/EVER (°). r: Pearson's correlation, s: Spearman's correlation



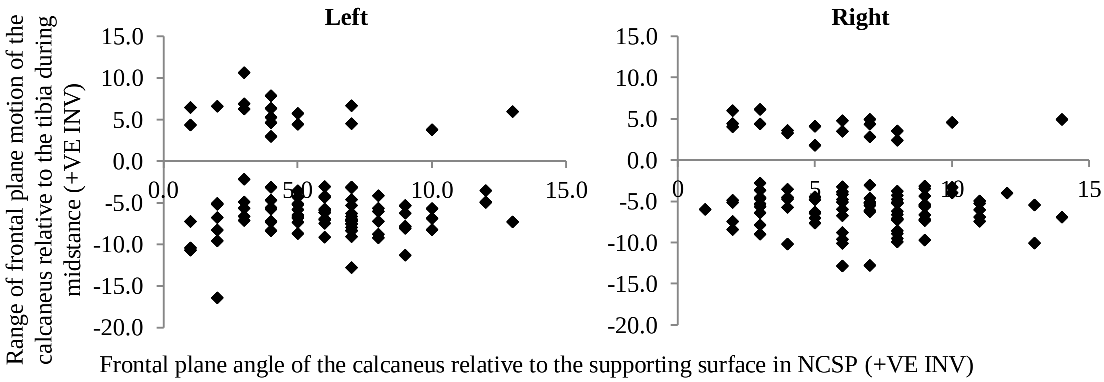
Figures 6.25a (left) and 6.25b (right): Frontal plane movement of the calcaneus relative to the tibia during the gait cycle in feet classified with a rearfoot varus. Black solid line represents mean, dashed grey lines represent standard deviation. Blue solid line represents angle of the calcaneus relative to the supporting surface in NCSP. Vertical red lines represent time of forefoot loading, heel lift and toe off.



Figures 6.25c (left) and 6.25d (right) presents a scatter plot of the correlation between the frontal plane angle of the calcaneus relative to the supporting surface in NCSP, and the frontal plane angle of the calcaneus relative to the tibia at heel lift in feet classified with a rearfoot varus.



Figures 6.25e (left) and 6.25f (right) presents a scatter plot of the correlation between the frontal plane angle of the calcaneus relative to the supporting surface in NCSP, and the peak angle of eversion of the calcaneus relative to the tibia during midstance in feet classified with a rearfoot varus.



Figures 6.25g (left) and 6.25h (right) presents a scatter plot of the correlation between the frontal plane angle of the calcaneus relative to the supporting surface in NCSP, and the range of frontal plane motion of the calcaneus relative to the tibia during midstance in feet classified with a rearfoot varus.

Discussion

From the cohort tested in this investigation, all feet with exception of one on the left and right were classified with a rearfoot varus. Therefore, it was not possible to compare feet classified as rearfoot varus to Root et al (1971, 1977) proposed normal foot. Since all participants in this investigation are asymptomatic this result questions whether a rearfoot varus deformity is a cause of injury. It also questions the clinical value of this examination. If almost all feet from a cohort as large as the one tested in this investigation are classified with a rearfoot varus, and only one is classified as normal it suggests that feet that are symptom free do not match the mechanical characteristic requirements proposed by Root et al (1977). This question what they proposed is representative of normality.

Root et al (1977) stated that the subtalar joint in a foot classified with a rearfoot varus will remain in an abnormally pronated position throughout midstance, and will only begin to supinate at heel lift. However, the results from this investigation demonstrate that feet classified with a rearfoot varus do not function exactly as Root et al 1977) proposed. Agreeably in feet classified with a rearfoot varus the calcaneus everted relative to the tibia for the majority of midstance, but it then inverted from reaching a peak angle of eversion for the remainder of midstance. This suggests that contrary to Root et al (1977) it was in a less everted position at heel lift, than during midstance.

This is in agreement with the results from many (Hunt et al 2001a, McPoil and Cornwall 1996a, Nester et al 2006, Lundgren et al 2007, Simon et al 2006, Cornwall and McPoil 1999a, McPoil and Cornwall 1994, Leardini et al 2007). They all reported results similar to this investigation, describing that the calcaneus everted relative to the tibia for the majority of midstance, and then began to invert from reaching a peak angle of eversion during midstance. All participants included in these investigations (Hunt et al 2001a, McPoil and Cornwall 1996a, Nester et al 2006, Lundgren et al 2007, Simon et al 2006, Cornwall and McPoil 1999a, McPoil and Cornwall 1994, Leardini et al 2007) are also all asymptomatic. This suggests that in agreement with Nigg (2001), Hunt et al (2001a) and McPoil and Cornwall (1995) pronation, or eversion of the subtalar joint during midstance should not be classified as abnormal.

A key element of the Root et al (1977) description is that the angle measured from NCSP is believed to be able to predict the angle of the subtalar joint during midstance. However, the results from this investigation, McPoil and Cornwall (1994) and McPoil and Cornwall (1996a) demonstrate that there is a large difference between the angle of the calcaneus in the frontal plane relative to the tibia in NCSP, and the angle at heel lift or the peak angle of eversion during midstance. The correlation values from this investigation of s = <-0.158 (p = 0.06) on the left, and s

= <0.200 (p = 0.02) on the right emphasise the poor relationship between these two parameters.

Root et al (1977) proposed that the position of the foot during midstance incorporates any structural deformity of the rearfoot and forefoot. Therefore, they would propose that the subtalar joint may have had to pronate more than just the angle of the rearfoot in order to fully compensate for any deformity of the forefoot. This could initially be hypothesised to explain the very low correlation values described previously. Agreeably, a limitation of this hypothesis is that it has not combined the overall angle of the rearfoot and forefoot to estimate how much eversion should take place at the subtalar joint. Keenan and Bach (2006), Menz and Keenan (1997), and Keenan (1997) suggested the poor reliability, and questionable validity of the clinical measurement of NCSP may be why is cannot predict the movement of the subtalar joint during walking. For example, the results from Chapter 4, Section 4.2 indicate that the results of the random affects ANOVA the main causes of error in the examination of NCSP is from random error (<2.9°), and assessor error (<2.2°). Therefore, even with improvements in the ability of the clinician there will still be residual random error incurred. This will make it inherently difficult to achieve the required preciseness of the examination.

Overall, this hypothesis is accepted. This is because in the majority of feet classified with a rearfoot varus the calcaneus everted relative to the tibia during midstance. However, the calcaneus did not evert relative to the tibia throughout midstance. Also, since all participants are symptom free the clinical value of this examination is questionable since if it does not infer deformity or pathology.

6.5.5 Hypothesis 4 - A foot classified with a rearfoot valgus deformity defined from static examination will pronate at the subtalar joint throughout the stance phase of the gait cycle. This is compared to a normal foot which will pronate at the subtalar joint during the contact phase, and supinate at the subtalar joint during midstance and propulsion.

No feet were classified as a rearfoot valgus deformity from static examination. Therefore, further descriptive, and statistical analysis could not be conducted.

Descriptive Analysis (+ve angle INV)	**Angle at NCSP in feet classified with a Rear Foot valgus (Data set A)**	
	Left	**Right**
No. of feet (n)	0	0
Mean (°)	#	#
SD (°)		
95% CI (°)		
Max INV angle (°) Min INV angle (°)		

Table 6.27 describes the mean frontal angle of the calcaneus relative to supporting surface in NCSP in feet classified with a rearfoot valgus from static examination (Data set A). The Max/Min angle of INV/EVER(°).

Discussion

As no feet were classified with a rearfoot valgus in this investigation it strongly indicates that in consideration of the size of the cohort tested this type of foot deformity is rare in an asymptomatic population. This is in agreement with Helliwell et al (2007), Lorimer et al (2002), and Michaud (1997) who have reported that patients diagnosed with chronic conditions such as rheumatoid arthritis, diabetes or currently suffering from musculoskeletal injuries such as plantar fasciitis are also commonly classified with a rearfoot valgus deformity.

6.5.6 Hypothesis 5 -The normal range, or angle of dorsiflexion that should be measured at the first metatarsophalangeal joint in a static examination, and during propulsion in the normal foot is between 65°- 75°. In feet that dorsiflex to less than 65° at the first metatarsophalangeal joint during propulsion, the subtalar joint will be in a pronated position during midstance and propulsion.

In the static examination of the first metatarsophalangeal joint most feet were classified with more than 65° range of dorsiflexion (left: >65° n= 92 (93%)), than less than 65° range of dorsiflexion (left: <65° n=7 (7%)) (Table 6.28).

Descriptive analysis (+ve ROM DF)	**Left**		**Right**	
	<65°	**>65°**	**<65°**	**>65°**
No. of feet (n)	*n=7 (7%)*	*n=92 (93%)*	*n=14(15%)*	*n=81(85%)*
Mean (°)	55.0	80.5	55.4	82.5
SD (°)	*4.1*	*11.7*	*6.0*	*9.7*
95% CI (°)	*51.2- 58.7*	*78.1- 82.9*	*51.8- 58.8*	*80.4- 84.6*
Max DF angle (°)	*60.0*	*115.0*	*60.0*	*100.0*
Min DF angle (°)	*50.0*	*65.0*	*40.0*	*65.0*

Table 6.28 describes the mean range of dorsiflexion at the first metatarsophalangeal joint measured from static examination (Data set A). All feet were classified as <65° or >65° range of dorsiflexion at the first metatarsophalangeal joint. The Max/Min range of DF/PF, (°).

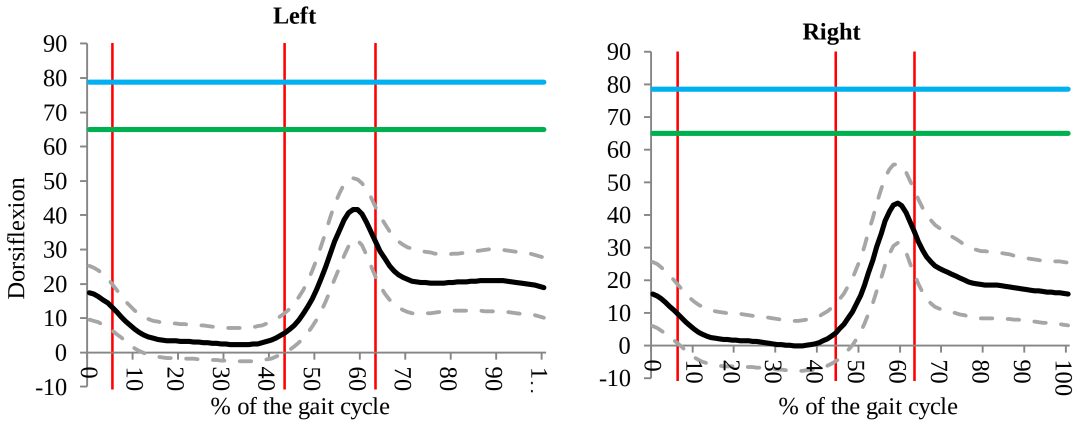
In the majority of feet classified with <65°, or >65° range of dorsiflexion at the first metatarsophalangeal joint from static examination the hallux is dorsiflexed less than 65° relative to the medial forefoot for both gait parameters (Table 6.29, Figures 6.26a-6.26d). For toe off (left: <65° classification = 26.9° (SD=10.8°), >65° classification = 33.5° (SD = 9.5°)), and the peak angle of dorsiflexion is less than 65° during propulsion (left: <65° classification = 39.3° (SD= 9.2°), >65° classification = 45.3° (SD = 8.7°)) (Table 6.29, Figures 6.26a-6.26d). In 3 feet on the left classified with more than 65°, and 1 foot on the right classified with less than 65° from static examination dorsiflexed more than 65° for any gait parameter during propulsion.

In feet classified with >65°,the hallux was dorsiflexed <6.6° (SEM =3.4), (p=0.03) on the left and <4.2° (SEM =3.4), (p= 0.03) on the right more relative to the medial forefoot at toe off, and the peak angle of dorsiflexion during propulsion than feet classified with <65°. The mean value for both classifications of feet and gait parameters is less than 65°.There is some inter-participant variation in the sagittal plane angle of the hallux relative to the medial forefoot for both gait parameters. Standard deviation values are large with SD= >8.7° on the left, and SD= >11.7° on the right, although, the direction is consistent with dorsiflexion across nearly all feet.

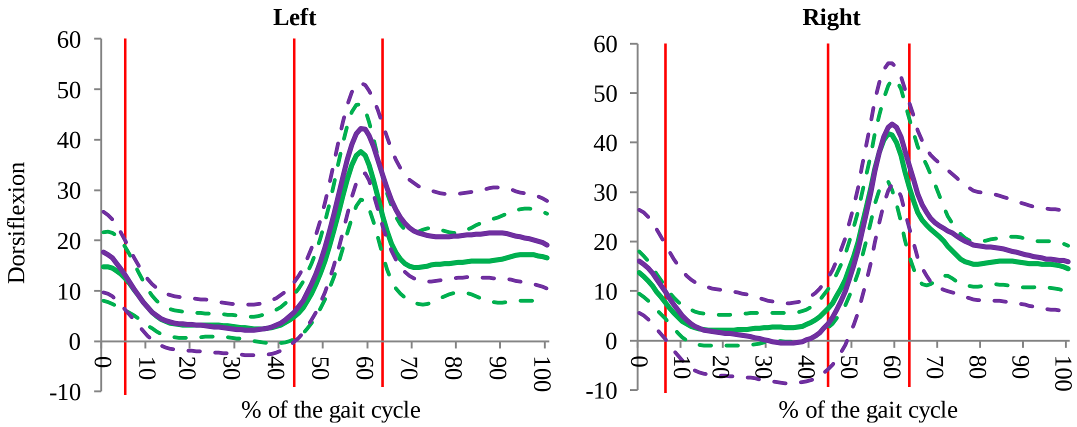
Contrary to the hypothesis in feet classified with <65° range of dorsiflexion the calcaneus was less everted relative to the tibia during midstance, or propulsion than feet classified with >65° (p= >0.125 on the left and p= >0.07 on the right) (Table 6.29, Figures 6.26e-6.26f).

Segment	Gait Parameter	Descriptive Analysis (+ve angle/ ROM DF/INV)	Left		Right	
			<65°	>65°	<65°	>65°
Hallux-Medial FF		No. of feet	*n=9*	*n=91*	*n=14*	*n=81*
	Angle at toe off	Mean *(°)*	26.9	33.5	32.3	35.3
		SD (°)	*10.8*	*9.5*	*12.8*	*13.1*
		95% CI (°)	*18.6- 35.2*	*31.5- 35.5*	*24.8- 39.7*	*32.4- 38.2*
		Max DF angle (°)	*47.3*	*69.0*	*66.3*	*57.3*
		Min DF angle (°)	*15.5*	*15.5*	*15.7**	*0.1*
		<65° v's >65°	***0.03***		*0.07*	
	Peak angle of DF during propulsion	Mean *(°)*	39.3	45.3	43.4	47.6
		SD (°)	*9.2*	*8.7*	*11.6*	*11.7*
		95% CI (°)	*32.2- 46.4*	*43.4- 47.1*	*36.7- 50.1*	*44.9- 50.2*
		Max DF angle (°)	*57.0*	*75.0*	*72.4*	*64.3*
		Min DF angle (°)	*26.1*	*26.1*	*23.8***	*14.9*
		<65° v's >65°	***0.02***		***0.03***	
Calcaneus-Tibia	ROM during midstance	Mean *(°)#*	-2.1	-4.6	-2.4	-4.5
		SD (°)	7.5	5.4	5.8	4.2
		95% CI (°)	-7.9- 3.6	-5.7- -3.5	-5.8- 0.9	-5.5- -3.6
		No .of feet INV ROM (n, %)	*n=2 (22%)*	*n=16 (18%)*	*n=5 (36%)*	*n=13 (16%)*
		Max INV ROM (°)	*13.9*	*10.6*	*5.9*	*6.1*
		Min INV ROM (°)	*6.9*	*2.9*	*2.8*	*1.8*
		No. of feet EVER ROM (n, %)	*n=7 (88%)*	*n=73 (82%)*	*n=9 (64%)*	*n=68 (84%)*
		Max EVER ROM(°)	*-7.4*	*-16.5*	*-12.8*	*-12.9*
		Min EVER ROM (°)	*-3.1*	*-2.2*	*-3.5*	*-2.8*
		<65° v's >65°	0.125		0.07	
	ROM during propulsion	Mean *(°)*	10.6	9.7	9.7	11.4
		SD (°)	*2.4*	*5.4*	*5.1*	*3.4*
		95% CI (°)	*8.8- 12.4*	*8.6- 10.9*	*6.7- 12.6*	*10.7- 12.2*
		No. of feet INV ROM (n, %)	*n=99 (100%)*	*n=86 (97%)*	*n=14 (100%)*	*n=80 99%)*
		Max INV ROM (°)	*13.5*	*30.7*	*16.1*	*20.2*
		Min INV ROM (°)	*5.9*	*3.1*	*3.6*	*2.9*
		No. of feet EVER ROM (n, %)	-	*n=3 (8%)*	-	*n=1 (1%)*
		Max EVER ROM(°)	-	*-15.9*	-	*-3.0*
		Min EVER ROM (°)	-	*-4.2*	-	-
		<65° v's >65°	0.202		0.151	

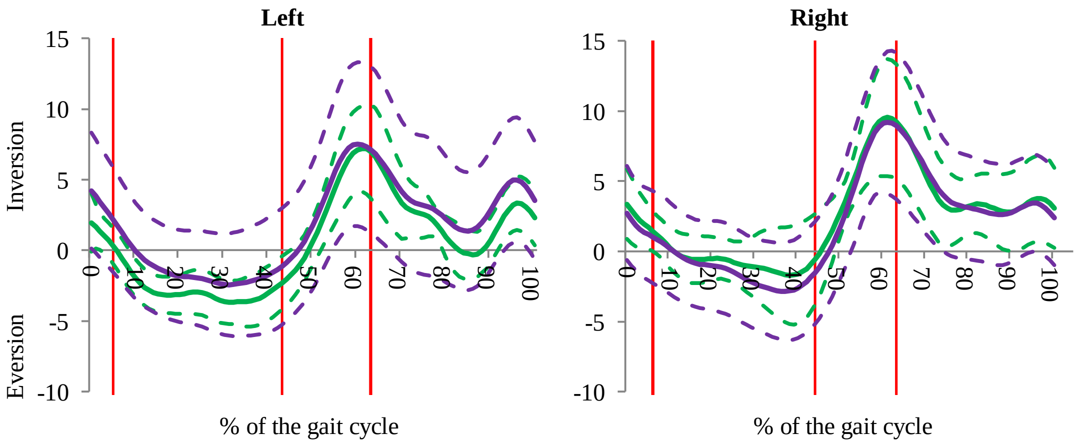
Table 6.29 describes the mean sagittal plane angle of the hallux relative to the medial forefoot at toe off, and during propulsion and the range of frontal plane motion of the calcaneus relative to the tibia during midstance, and propulsion with comparison (p) between classifications of feet (<65° versus >65°). The number of feet displaying range of INV/EVER (n, %). The Max/Min range or angle of DF, INV/EVER (°).* No. of feet that demonstrate a PF angle at TO: <65° n=1 (right). ** No. of feet that demonstrate a PF angle at the peak angle of DF during propulsion: <65° n=1(right).



Figures 6.26a (left) and 6.26b (right): Sagittal plane movement of the hallux relative to the medial forefoot during the gait cycle. Black solid line: mean, dashed grey lines: standard deviation. Blue solid line: mean range of dorsiflexion at the first metatarsophalangeal joint measured from static examination. Green solid line: 65° range of dorsiflexion. Vertical red lines represent time of forefoot loading, heel lift and toe off.



Figures 6.26c (left) and 6.26d (right): Sagittal plane movement of the hallux relative to the medial forefoot during the gait cycle. Purple line : >65°. Green line: <65°. Solid line represents mean, and dashed lines represent standard deviation. Vertical red lines represent time of forefoot loading, heel lift and toe off.

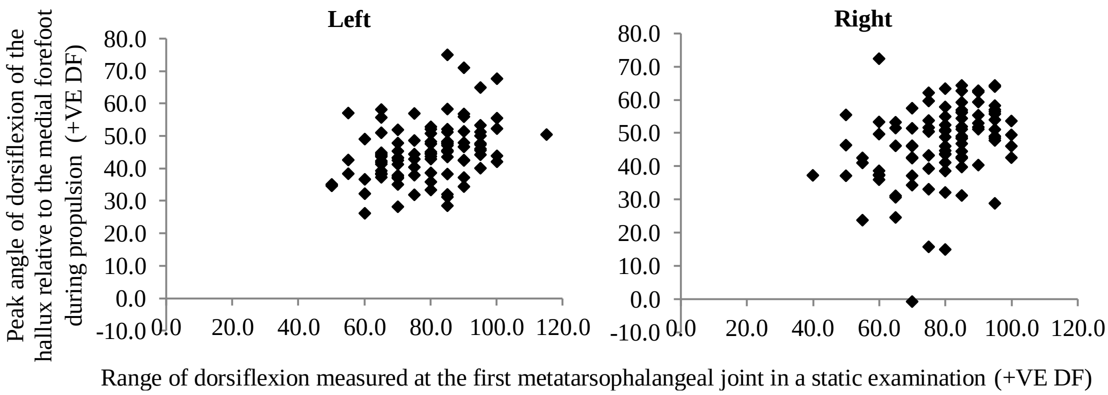


Figures 6.26e (left) and 6.26f (right): Frontal plane movement of the calcaneus relative to the tibia during the gait cycle. Purple line : >65°. Green line: <65°. Solid line represents mean, and dashed lines represent standard deviation. Vertical red lines represent time of forefoot loading, heel lift and toe off.

All s values indicate low to moderate correlation between the range of dorsiflexion at the first metatarsophalangeal joint measured from static examination, and the sagittal plane angle of the hallux relative to the medial forefoot during propulsion (left: s = <0.382 (p = <0.001), right: s = <0.390 (p = <0.001)) (Table 6.30, Figures 6.26h-6.26g).

Static Examination	Gait Parameter for Hallux- Medial FF	Correlation (s, (p))	
		Left (n=100)	**Right (n=95)**
Range of dorsiflexion at the 1st MPJ measured from static examination (Data set A)	Angle at toe off	0.335 (<**0.001**)	0.379 (<**0.001**)
	Peak angle of DF during propulsion	0.382 (<**0.001**)	0.390 (<**0.001**)

Table 6.30 presents the results of Spearman's correlations (s (p)) between the range of dorsiflexion at the first metatarsophalangeal joint measured from static examination (Data set A) and the sagittal plane angle of the hallux relative to the medial forefoot at toe off and peak angle of dorsiflexion during propulsion. s: Spearman's correlation



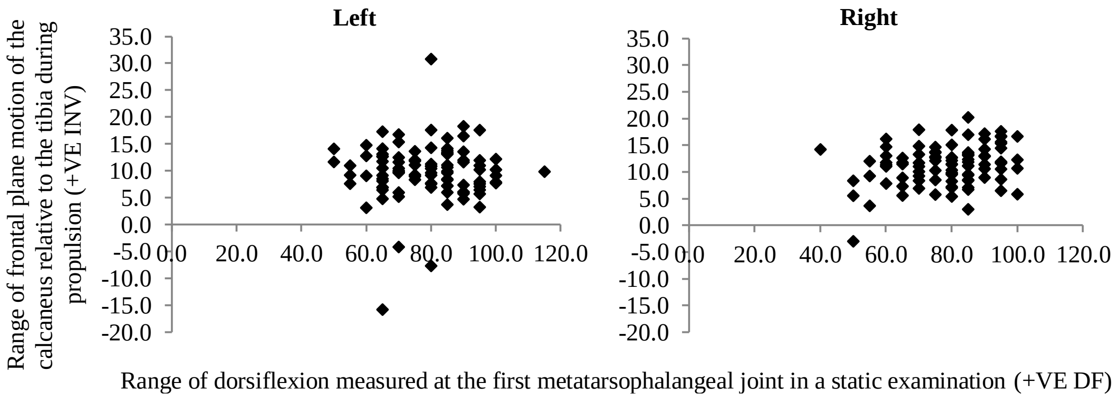
Figures 6.26h (left) and 6.26g (right) presents a scatter plot of the correlation between the range of dorsiflexion measured at the first metatarsophalangeal joint in a static examination, and the peak angle of dorsiflexion of the hallux relative to the medial forefoot during propulsion

Similar scatter plots of the correlation between the range of dorsiflexion measured at the first metatarsophalangeal joint in a static examination, and the sagittal plane angle of the hallux relative to the medial forefoot at toe off were created.

All s values indicate no to low correlation between the sagittal plane angle of the hallux relative to the medial forefoot during propulsion and the range of frontal plane motion of the calcaneus relative to the tibia during midstance, and propulsion (left:s = <-0.09 (p = 0.167), right:s = <0.247 (p = 0.008) on the right) (Table 6.31, Figures 6.26i-6.26j)

Gait parameter for Hallux-Medial FF	Gait parameter for Calc-Tibia	Correlation (s, (p))	
		Left (n=98)	Right (n=95)
Angle at toe off	ROM during midstance	-0.06 (0.284)	0.119 (0.125)
Peak angle of DF during propulsion		0.02 (0.419)	0.08 (0.271)
Angle at toe off	ROM during propulsion	0.04 (0.334)	0.169 (**0.05**)
Peak angle of DF during propulsion		-0.09 (0.204)	0.247 (**0.008**)

Table 6.31 presents the results of Spearman's correlations (s (p)) between the sagittal plane angle of the hallux relative to the medial forefoot at toe off and the peak angle of dorsiflexion during propulsion and the range of frontal plane motion of the calcaneus relative to the tibia during midstance and propulsion. s:Spearman's correlation



Figures 6.26i (left) and 6.26j (right) presents a scatter plot of the correlation between the range of dorsiflexion measured at the first metatarsophalangeal joint in a static examination, and the range of frontal plane motion of the calcaneus relative to the tibia during propulsion

Similar scatter plots of the correlation between the range of dorsiflexion measured at the first metatarsophalangeal joint in a static examination, and the range of frontal plane motion of the calcaneus relative to the tibia during propulsion were created. The primary movement of interest of the calcaneus relative to the tibia, and how it may or may not affect the movement of the first metatarsophalangeal joint is during propulsion.

Discussion

In agreement with Root et al (1977), and others (Joseph 1954, Hopson et al 1995, Van Gheluwe et al 2006 and Scherer et al 2006) the range of dorsiflexion measured in the non weight bearing static examination of the first metatarsophalangeal joint is greater than 65° in the majority of asymptomatic feet. Other investigations (Hopson et al 1995, Munteanu and Bassed 2006), have reported that the range of dorsiflexion measured in a weight bearing static based examination of the first metatarsophalangeal joint was also greater than 65°.

Root et al (1977) proposed that the first metatarsophalangeal joint must be dorsiflexed to 65° at toe off. However, the results from this investigation, and others (Halstead and Redmond 2006, Turner et al 2007, Van Gheluwe et al 2006, Nawoczenski et al 1999, Carson et al 2001 and Simon et al 2006) report that contrary to Root et al (1977) the hallux is not dorsiflexed to 65° relative to the medial forefoot or first metatarsal during propulsion. This indicates that the first metatarsophalangeal joint does not require its full range of dorsiflexion during walking. Even in feet classified with more than 65° from static examination the hallux was dorsiflexed only <35.3° (SD = 13.1°) relative to the medial forefoot at toe off. Therefore, the influence of body weight and internal forces when walking is different to when this joint is examined statically.

All participants included in this, and other (Halstead and Redmond 2006, Van Gheluwe et al 2006, Nawoczenski et al 1999, Carson et al 2001, Simon et al 2006, MacWilliams et al 2003) investigations are asymptomatic. This strongly suggests that 65° of dorsiflexion is not required for the first metatarsophalangeal joint to be symptom, or deformity free. Although no x-ray images were taken of any of the feet included in this investigation or is used in any of the other investigations (Halstead and Redmond 2006, Van Gheluwe et al 2006, Nawoczenski et al 1999, Simon et al 2006, Carson et al 2001 and MacWilliams et al 2003) to confirm the visual inspection.

The lack of a relationship between these static and all dynamic parameters is further emphasised with $s = <0.382$ ($p = <0.0001$) on the left, and $s = 0.390$ ($p = <0.001$) on the right. These results are in agreement with Halstead and Redmond (2006) who reported similar correlation values of $r = 0.186$ ($p = 0.325$) between these parameters. They reported mean values of 55.0° (SD = 10.7°) for the non-weight bearing static examination, but only 36.9° (SD = 7.9°) for the angle at toe off. Van Gheluwe et al (2006) and Turner et al (2007) described moderately stronger correlation values of $r = 0.45$ (Van Gheluwe et al 2006), and $r = 0.61$ (Turner et al 2007). Although, both investigations report a similar large difference between the static examination measurement and the same gait parameters. The results from this investigation, and Van Gheluwe et al (2006) indicate that in feet classified with greater than 65° (or greater than 70° (Van Gheluwe et al 2006)) range of dorsiflexion from a static non-weight bearing examination of the first metatarsophalangeal joint the hallux will be significantly more dorsiflexed for most of the gait parameters tested, than feet classified with less than 65° (or less than 70° (Van Gheluwe et al 2006)). However, the difference in the measurements from the static examination in feet classified with less than 65°, or more than 65° are much greater than the difference for either of the gait parameters. Turner et al (2007) reported that individuals presenting with a chronic disease used a greater percentage of the range of dorsiflexion at the first metatarsophalangeal joint that was measured from static examination during walking. They described how during walking asymptomatic participants used only 69.1% of the range of dorsiflexion measured from the static examination. This significantly increased to 84.7% in patients with more chronic complications associated with diabetes, such as neuropathic ulceration. This indicates that with a decreasing health status the static examination of a joint is maybe a more useful indicator of the movement of this joint during walking. One of the possible reasons for this improvement in the relationship between these parameters could be because there is considerably greater variability within an asymptomatic population, than there is with the diseased or pathological foot. There will also be physical changes to the bone and soft tissue structures within the foot and leg that will affect their movement. Although, Turner et al (2007) did not report a similar trend for other joints (for example the range of frontal plane motion of the ankle joint) of the foot, indicating that it could be joint specific.

Another key factor to consider which was originally highlighted by Joseph (1954), is the large inter-participant variation in the movement of the first metatarsophalangeal joint in the sagittal plane in both static examination, and during walking. Joseph (1954) suggested that such variation indicates that it is not possible to specify a value that represents limits of the movement of this joint. However, Root et al (1977) failed to realise the importance of this, and focused on the achievement of specific values to represent the normal foot. The results from this investigation, and others (Halstead and Redmond 2006, Hopson et al 1995, Nawoczenski et al 1999, Munteanu and Bassed 2006, Harradine and Bevan 2000) strongly indicate that a range in values to represent the sagittal plane angle of the first metatarsophalangeal joint at toe off in the asymptomatic foot maybe more useful. This could be proposed to be between 36°-50° and not 65°.

Root et al (1977) proposed that if the first metatarsophalangeal joint is unable to dorsiflex to 65° during propulsion there is a structural deformity of this joint. Joint deformities such as hallux limitus will commonly cause pain, swelling and structural damage to this joint. This restriction in the range of dorsiflexion was hypothesised by Root et al (1977) to be caused by abnormal pronation of the subtalar joint, which would create a functional hallux limitus. Indeed, Harradine and Bevan (2000) reported that with a more everted position of the calcaneus, the range of dorsiflexion at the first metatarsophalangeal joint decreased significantly. However, in this investigation the calcaneus everted relative to the tibia during midstance and then inverted during propulsion in most feet classified with less than 65°, or more than 65° of dorsiflexion from static examination of the first metatarsophalangeal joint. There was also no significant difference in the movement of the calcaneus relative to the tibia between classifications of feet. This same pattern of movement was reported by many (Cornwall and McPoil 1999a, Hunt et al 2001a, Moseley et al 1996, Leardini et al 2007, Kitaoka et al 2006, Lundgren et al 2007). These investigations have all used asymptomatic participants with no identifiable structural deformity of the first metatarsophalangeal joint. This suggests that in agreement with McPoil and Hunt (1995), and Nigg (2001) pronation of the subtalar joint during midstance is not a cause of structural deformity, or injury to soft and bony tissues of the first metatarsophalangeal joint.

Overall, this hypothesis is rejected. This is because firstly the static examination of the range of dorsiflexion at the first metatarsophalangeal joint cannot predict the sagittal plane angle of the hallux relative to the medial forefoot at toe off, or propulsion. Secondly, in nearly all of the asymptomatic feet included in this investigation the hallux did not dorsiflex to 65° relative to the medial forefoot at toe off, or during propulsion. Thirdly, eversion of the calcaneus relative to the tibia during midstance is not a cause of deformity, or a limitation in the range of dorsiflexion at the first metatarsophalangeal joint.

6.5.7 Hypothesis 6.a. - A foot classified with a plantarflexed first ray deformity defined from static examination will pronate at the subtalar joint, and supinate at the midtarsal joint during propulsion. This is compared to a normal foot which will supinate at the subtalar joint, and pronate at the midtarsal joint during propulsion.

More feet were classified with a plantarflexed first ray (left: 83%, right: 84%), than no forefoot deformity (left: 17%, right: 16%).

In 97% of feet on the left and 99% of feet on the right classified with a flexible or rigid plantarflexed first ray, the calcaneus inverted relative to the tibia during propulsion (left: 9.4° (SD= 4.1°), right: 10.9° (SD= 3.9°)Table 6.32, Figures 6.27a and 6.27b)). This is a similar percentage of feet and range of inversion to feet classified with no forefoot deformity (left: 10.2° (SD = 8.7°), right: 12.1° (SD = 3.2°)) (Table 6.32).

In feet classified with a plantarflexed first ray, the range of frontal plane motion of the midfoot relative to the calcaneus during propulsion was 2.3° (SEM = 0.81), (p= 0.04) (flexible plantarflexed first ray) and 1.8° (SEM = 0.96), (p = 0.05) (rigid plantarflexed first ray) greater, than feet classified with no forefoot deformity on the right. However, contrary to the hypothesis in feet classified with no forefoot deformity the midfoot also inverted relative to the calcaneus during propulsion. This is demonstrated by the same movement pattern of the midfoot displayed in Figures 6.27c and 6.27d.

In contrast, on the left, the range and direction of frontal plane motion of the midfoot relative to the calcaneus during propulsion was similar in feet classified with a plantarflexed first ray (flexible and rigid) or no forefoot deformity (Figures 6.27c and 6.26d). For example, in feet classified with a plantarflexed first ray (flexible and rigid), the midfoot inverted (supinated) relative to the calcaneus in 56% of feet, and everted (pronated) in 44% of feet during propulsion. In feet classified with no forefoot deformity, the midfoot inverted (supinated) relative to the calcaneus in 44% of feet and everted (everted) in 56% of feet during propulsion.

Segment	Gait Parameter #	Descriptive Analysis (+ve ROM INV)	Left: No forefoot deformity	Left: Plantarflexed first ray deformity: Flexible	Left: Plantarflexed first ray deformity: Rigid	Left: Plantarflexed first ray deformity: Flexible and rigid	Right: No forefoot deformity	Right: Plantarflexed first ray deformity: Flexible	Right: Plantarflexed first ray deformity: Rigid	Right: Plantarflexed first ray deformity: Flexible and rigid
Calcaneus-Tibia	No. of feet		n=18	n=44	n=31	n=75	*n=15*	*n=57*	*n=20*	*n=77*
	ROM during propulsion	Mean (°)	10.2	10.3	8.1	9.4	12.1	10.9	10.6	10.9
		SD (°)	8.7	3.2	4.9	4.1	3.2	4.1	3.5	3.9
		95% CI (°)	5.8- 14.5	9.3- 11.3	6.3- 9.9	8.4- 10.3	10.3- 13.8	9.9- 12.1	9.0- 12.3	9.9- 11.8
		No. of feet INV ROM (n, %)	*n=17(94%)*	*n=44 (100%)*	*n=29 (94%)*	*n=73(97%)*	*n=15 (100%)*	*n=56(98%)*	*n=20(100%)*	*n=76 (99%)*
		Max INV ROM (°)	*30.7*	*17.5*	*15.3*	*15.3*	*16.9*	*20.2*	*16.1*	*20.2*
		Min INV ROM (°)	*6.0*	*4.7*	*3.1*	*3.1*	*6.2*	*2.9*	*3.6*	*2.9*
		No. of feet EVER ROM (n, %)	*n=1(6%)*	*0*	*n=2 (6%)*	*n=2(3%)*	*0*	*n=1(2%)*	*0*	*n=1 (1%)*
		Max EVER ROM (°)	*-15.8*	-	*7.7*	*7.7*	-	*-3.0*	-	*-3.0*
		Min EVER ROM (°)	-	-	*-4.2*	*-4.2*	-	-	-	-
		No FFD v's PF 1st ray (p)	0.07			0.521	0.482			0.138
Midfoot-Calcaneus	ROM during propulsion	Mean (°) *	-0.7	0.3	-0.2	0.1	0.8	3.1	2.6	2.9
		SD (°)	3.5	3.9	4.3	4.1	2.9	2.6	3.0	2.7
		95% CI (°)	-2.4- 1.1	-0.9- 1.5	-1.7- 1.4	-0.8- 1.0	-0.9- 2.4	2.4- 3.8	1.1- 4.1	2.3- 3.6
		No. of feet INV ROM (n, %)	*n=8 (44%)*	*n=27(61%)*	*n=15 (48%)*	*n=42(56%)*	*n=10 (67%)*	*n=49 (91%)*	*n=16 (84%)*	*n=65 (89%)*
		Max INV ROM (°)	*5.3*	*6.6*	*8.9*	*8.9*	*5.1*	*8.2*	*7.8*	*8.2*
		Min INV ROM (°)	*1.0*	*1.8*	*1.3*	*1.3*	*1.1*	*1.1*	*1.2*	*1.1*
		No. of feet EVER ROM (n, %)	*n=10 (56%)*	*n=17 (39%)*	*n=16 (52%)*	*n=33 (44%)*	*n=5 (33%)*	*n=5 (9%)*	*n=3 (16%)*	*n=8 (11%)*
		Max EVER ROM (°)	*-5.2*	*-9.3*	*-8.5*	*-9.3*	*-3.9*	*-3.5*	*-3.5*	*-4.7*
		Min EVER ROM (°)	*-1.9*	*-1.5*	*-2.1*	*-1.5*	*-2.6*	*-2.2*	*-2.2*	*-0.9*
		No FFD v's PF 1st ray (p)	0.613			0.361	**p = 0.03** No FFD v's PF 1st ray (F) p = 0.004 No FFD v's PF 1st ray (R) p = 0.05**			**0.005**

Table 6.32 describes the mean range of frontal plane motion of the calcaneus relative to the tibia and the midfoot relative to the calcaneus during propulsion in feet classified with a plantarflexed first ray deformity (flexible and/or rigid), or no forefoot deformity with comparison between classifications of feet. The number of feet displaying range of INV/EVER (n, %). The Max/Min range of INV/EVER (°). * Right: Midfoot-Calc ROM during propulsion data missing from plantarflexed first ray deformity flexible and rigid classification (n=4/77). Plantarflexed first ray deformity flexible classification (n=3/57). Plantarflexed first ray deformity rigid classification (n=1/20). ** Significant p value for Krushal-Wallis test, post hoc tests conducted with Bonferroni correction (significant p value = <0.167)

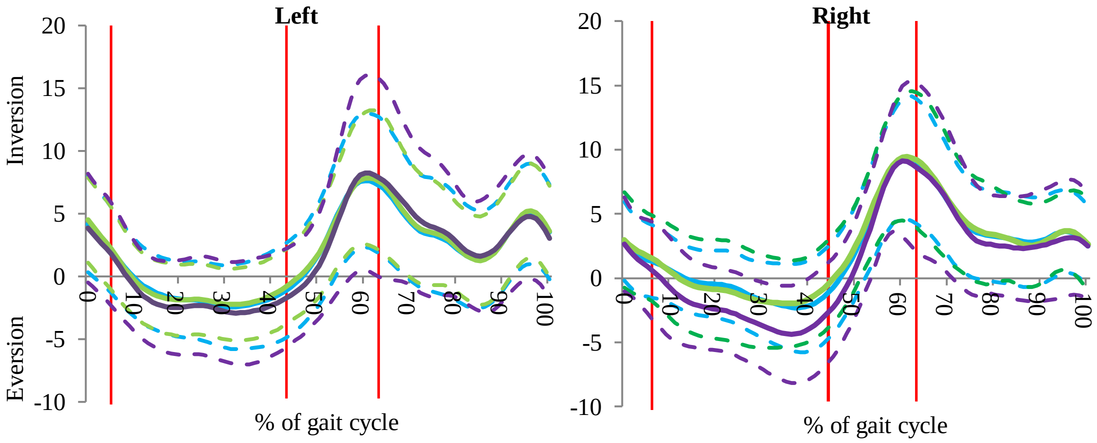
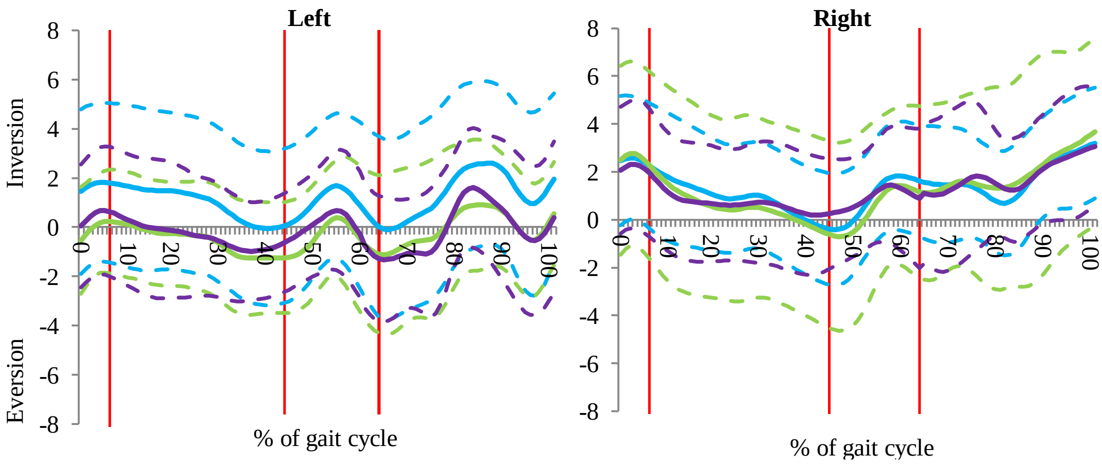


Figure 6.27a (left) and 6.27b (right): Frontal plane movement of the calcaneus relative to the tibia during the gait cycle. Blue line: flexible plantarflexed first ray. Green line: rigid plantarflexed first ray. Purple line: no forefoot deformity. Solid line represents mean, dashed lines represent standard deviation. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.



Figures 6.27c (left) and 6.27d (right): Frontal plane movement of the midfoot relative to the calcaneus during the gait cycle. Blue line: flexible plantarflexed first ray. Green line: rigid plantarflexed first ray. Purple line: no forefoot deformity. Solid line represents mean, dashed lines represent standard deviation. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

Discussion

The examination of the first ray was proposed by Root et al (1977) and is described by podiatrists in Chapter 4, Section 4.2 as an important static examination of the foot. Some (McPoil et al 1988), have reported the incidence of a plantarflexed first ray deformity in an asymptomatic population. Others (Scherer et al 2006, Roukis et al 2006) have attempted to simulate increased plantarflexion of the first ray, and measure how the kinematic movement and function of the foot changes. However, there is very little literature (Hamill et al 1989, McPoil and Cornwall 1996b) that has tested the Root et al (1977) description of the movement of a foot classified with a plantarflexed first ray.

McPoil et al (1988) reported that 14.7% of the 116 feet examined were classified with a plantarflexed first ray deformity. In contrast, this investigation reports that 83% of feet on the left were classified with a plantarflexed first ray. There were more feet classified with a flexible (left: 59%) than a rigid (left: 41%) plantarflexed first ray deformity. There were a similar number and percentage of feet on the right.

Root et al (1977) proposed that a foot classified with a plantarflexed first ray deformity would be pre-disposed or present with injury. This is because to compensate for this structural deformity, they proposed that the subtalar joint will have to pronate during propulsion, when it should be supinating. However, the large percentage of feet that were classified with a plantarflexed first ray deformity in this investigation, and to a lesser extent in McPoil et al (1988) questions this proposed relationship to injury, as all participants are asymptomatic.

The results from this investigation demonstrate that feet classified with a plantarflexed first ray deformity do not function as Root et al (1977) proposed. There is little difference in the kinematic movement of feet classified with a plantarflexed first ray deformity, or no forefoot deformity. In the majority of feet classified with a plantarflexed first ray deformity the calcaneus inverted relative to the tibia during propulsion. Thus, indicating that contrary to Root et al (1977) the subtalar joint is supinating, not pronating during propulsion. Feet classified with no forefoot deformity also inverted during this phase, which is a similar range of motion to feet classified with a plantarflexed first ray deformity.. For example, the range of frontal plane motion of the calcaneus relative to the tibia in feet classified with a plantarflexed first ray (flexible and rigid) was 9.4° (SD = 4.1°) on the left and 10.9° (SD =3.9°) on the right. This is similar to feet classified with no forefoot deformity with 10.2° (SD = 8.7°) on the left and 12.1° (SD = 3.2°) on the right.

These results are supported by Leardini et al (2007) and others (Cornwall and McPoil 1999a, Moseley et al 1996, Rattanaprasert et al 1999, Hunt et al 2001a, Arndt et al 2004, Lundgren et al 2007 and Simon et al 2006). They report that the calcaneus inverted between 7° to 10° relative to the tibia (or talus) during propulsion. Although these investigations (Leardini et al 2007, Cornwall and McPoil 1999a, Moseley et al 1996, Rattanaprasert et al 1999, Hunt et al 2001a, Arndt et al 2004, Lundgren et al 2007, Simon et al 2006) have not classified feet according to any first metatarsal deformity from static examination, all participants were asymptomatic.

Root et al (1977) proposed that the movement of the midtarsal joint during the gait cycle in the normal foot is predominantly dependent on the movement of the subtalar joint. However, during propulsion and contrary to Root et al (1977) the calcaneus inverted (supinated) relative to the tibia in most feet classified with a plantarflexed first ray deformity., This movement of the subtalar joint is what Root et al (1977) proposed will occur in the normal foot. Therefore, it would suggest that the movement of the midtarsal joint in feet classified with a plantarflexed first ray, should be as Root et al (1977) described in the normal foot.

However, contrary to Root et al (1977) in the majority of feet classified with a plantarflexed first ray deformity or no forefoot deformity the midfoot inverted relative to the calcaneus. Thus, the midtarsal joint supinates during propulsion. There is however some inter-participant variation in the range and direction of frontal plane motion of the midfoot relative to the calcaneus during propulsion. The extent of this variation is similar in feet classified with, or without a plantarflexed first ray.

The technique used by this, and other (Leardini et al 2007, DeMits et al 2012, Allen et al 2004, Nester et al 2007) investigations to measure the movement of the midfoot is different to Root et al (1977) description of the midtarsal joint. Most notably, Root et al (1977) only described the movement of this region of the foot around its proposed two axes or rotation

The classification of the mobility of the first ray deformity was described by podiatrists in Chapter 4, Section 4.2 as an integral part of this examination protocol. However, feet classified with a rigid or flexible plantarflexed first ray deformity function very similar. The difference between these classifications of feet is small and not significant (left: $p = >0.07$ and right: $p = >0.521$). This questions whether the mobility of the first ray can realistically influence the movement of joints proximal to it. However, Wolf et al (2008) and Pohl et al (2006) proposed that there are coupling mechanisms between and within the joints of the rear, mid and forefoot. Therefore, a limitation or excessive movement of one will affect the movement of other joints. This indicates that if there is a difference in the mobility of the first ray it could be important in determining the function of a foot. However, clinical examination techniques have here failed to detect a difference in the dynamic function, and are therefore of questionable clinical value.

Overall, hypothesis 6.a is rejected. This is because feet classified with a plantarflexed first ray deformity do not function as Root et al (1977) proposed and instead function very similar to how feet classified with no structural deformity of the forefoot function. Root et al (1977) description of how feet classified with no forefoot deformity is also incorrect.

6.5.8 Hypothesis 6.b - A foot classified with a dorsiflexed first ray deformity defined from static examination will not dorsiflex more than 65° at the first metatarsophalangeal joint during propulsion. This is compared to a normal foot which will dorsiflex between 65-75° at the first metatarsophalangeal joint during propulsion.

All feet classified with a dorsiflexed first ray were categorised as flexible deformities.

In feet classified with a dorsiflexed first ray, the hallux did not dorsiflex more than 65° relative to the medial forefoot at the angle of toe off (left: 33.6° (SD=3.5°)), or the peak angle of dorsiflexion (left: 42.5° (SD=4.3°) during propulsion (Table 6.32, Figures 6.28a-6.28b). However, in feet classified with no forefoot deformity the hallux did not dorsiflex more than 65° relative to the medial forefoot for any of the gait parameters (Table 6.32, Figures 6.28-6.28b). There was no difference (left: $p = >0.172$, right: $p = >0.218$) between those feet classified with or without a dorsiflexed first ray deformity for any of the gait parameters tested. Figures 6.28a-6.28b highlight how both classifications of feet demonstrated the same movement pattern throughout the gait cycle.

There is greater inter-participant variation between feet classified with no forefoot deformity (right: SD = <17.2° and left: SD = <10.8°) than for feet classified with a dorsiflexed first ray (right: SD = <10.8° and left: SD = <7.3°) (Table 6.32)). Although, the 95% confidence intervals for all gait parameters are of a similar range for both classifications of feet. For example the 95% confidence interval for the angle at toe off in feet classified with a dorsiflexed first ray is 29.9°- 37.3° (left). For feet classified with no forefoot deformity the 95% confidence interval = 25.2°- 36.3° (left). There are similar values for the right.

Segment	Gait Parameter	Descriptive Analysis (+ve angle DF)	Left		Right	
			No forefoot deformity	**Dorsiflexed 1st ray**	**No forefoot Deformity**	**Dorsiflexed 1st ray**
Hallux-MedFF	No. of feet (n)		n=17	n=6	*n=14*	*n=7*
	Angle at toe off	Mean (°)	30.7	33.6	29.4	35
		SD (°)	*10.8*	*3.5*	*17.2*	*10.1*
		95% CI (°)	*25.2- 36.3*	*29.9- 37.3*	*19.4- 39.3*	*25.7- 44.3*
		Max DF angle(°)	*50.6*	*38.3*	*51.7*	*49.9*
		Min DF angle (°) #	*15.5*	*27.7*	*10.5*	*22.9*
		No FF D v's DF 1st Ray p	0.172 *		0.218	
	Peak angle of DF during propulsion	Mean (°)	*41.7*	*42.5*	*40.4*	*43.4*
		SD (°)	*10.6*	*4.3*	*16.0*	*10.8*
		95% CI (°)	*36.3- 47.2*	*37.9- 47.1*	*31.3- 48.7*	*33.3- 53.4*
		Max DF angle (°)	*64.9*	*50.0*	*56.3*	*59.3*
		Min DF angle (°)#	*26.1*	*38.2*	*23.7*	*30.6*
		No FF D v's DF 1st Ray p	0.435		0.334	

Table 6.32 describes the mean sagittal plane angle of the hallux relative to the medial forefoot at toe off and the peak angle of dorsiflexion during propulsion. The Max/Min angle of DF (°).* Levene's test for equality of variances: Not assumed (p = 0.040). In replacement the p value from the equal variances are not assumed independent t-test was used. This has used a different degrees of freedom (df = 20.9) for the calculation. # No. of feet that demonstrate a plantarflexed angle at TO/peak angle of dorsiflexion during midstance: right No FFD n=1/17.

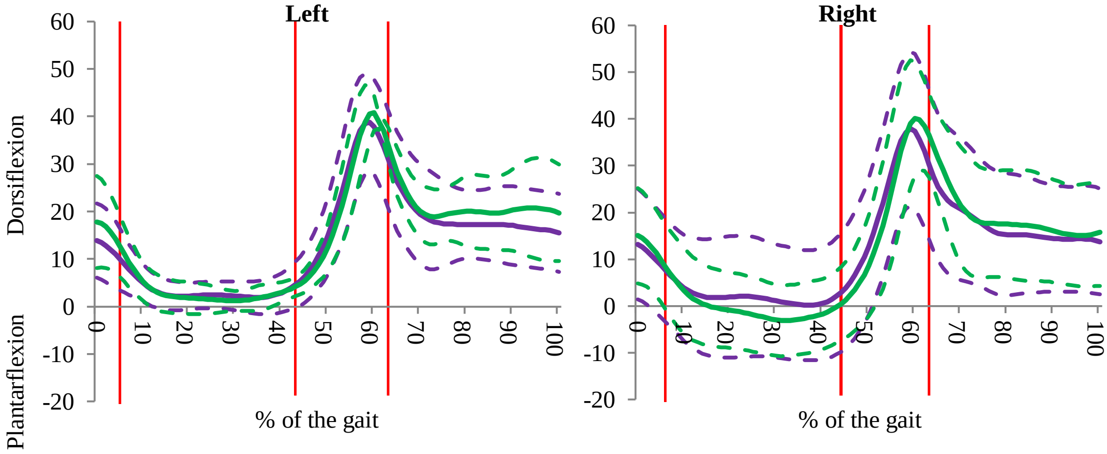


Figure 6.28a (left) and 6.28b (right): Sagittal plane movement of the hallux relative to the medial forefoot during the gait cycle. Green line: dorsiflexed first ray deformity. Purple line: no forefoot deformity. Solid line represents mean, dashed lines represent standard deviation. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

Discussion

The examination of the first ray was proposed by Root et al (1977) and is described by podiatrists in Chapter 4, Section 4.2 as an important static examination of the foot. However, most investigations (McPoil et al 1988, McPoil and Cornwall 1996b) report that no feet were classified with a dorsiflexed first ray. In consideration of the number of participants included in this investigation, and that only 6 feet on the left and 7 feet on the right were classified with a dorsiflexed first ray it would suggest this deformity of the foot is not common.

The hallux was not dorsiflexed relative to the medial forefoot to or more than 65° during propulsion, or at toe off in any feet classified with a dorsiflexed first ray deformity or no forefoot deformity. This is in agreement with Halstead and Redmond (2006) and others (Van Gheluwe et al 2006, Nawoczenski et al 1999, Simon et al 2006, Carson et al 2001). They report that the hallux was dorsiflexed relative to the first metatarsal between 36-50° during propulsion. All participants included in these investigations are as similar to this, asymptomatic. This indicates that Root et al (1977) description of what is proposed to represent the movement of the first metatarsophalangeal joint in the normal or abnormal foot during walking is incorrect. This suggests that a dorsiflexed first ray deformity does not cause, and is not associated with altered mechanical function of the first metatarsophalangeal joint.

All feet that were classified with a dorsiflexed first ray were categorised with a flexible deformity. The greater mobility of this structural deformity may make it is possible for the first ray to plantarflex, and be able to compensate for this deformity. In contrast, a dorsiflexed first ray categorised as rigid would be hypothesised to remain elevated from the supporting surface, and therefore is more attributed to the cause of injury or deformity. Roukis et al (1996) reported that when the first ray was placed in a fixed dorsiflexed position it significantly reduced the range of dorsiflexion at the first metatarsophalangeal joint. However, there are two key limitations to the investigation by Roukis et al (1996). They examined only 10 participants and the range of dorsiflexion was measured in RCSP. Therefore it cannot represent the change in the mechanical function of the foot as the heel lifts from the ground. This is proposed by Perry (1992) to be integral in helping to facilitate the movement of the first metatarsophalangeal joint during the gait cycle.

Overall, hypothesis 6.b is rejected. This is because although feet classified with a dorsiflexed first ray function as Root et al (1977) proposed, feet classified with this deformity function very similar to feet classified with no forefoot deformity. The results from this hypothesis also demonstrate that Root et al (1977) description of how feet classified with no forefoot deformity is incorrect.

6.5.9 Hypothesis 7.a - A foot classified with a forefoot valgus deformity defined from static examination will pronate at the subtalar joint, and supinate at the midtarsal joint during propulsion. This is compared to a normal foot which will supinate at the subtalar joint, and pronate at the midtarsal joint during propulsion.

More feet were classified with a forefoot valgus using the 1-5 metatarsal assessment (right: n=35), than the 2-4 metatarsal assessment (right: n=14) (Table 6.34).

Descriptive analysis (+ve angle INV)	Feet classified as forefoot valgus			
	2-4 metatarsal assessment		1-5 metatarsal assessment	
	Left	Right	Left	Right
No. of feet (n)	n=13	n=14	n=20	n=35
Mean (°)	-4.5	-4.6	-3.6	-4.1
SD (°)	*2.2*	*2.8*	*2.6*	*2.7*
95% CI (°)	*-5.8- -3.1*	*-6.2- -2.9*	*-4.8- -2.4*	*-5.0- -3.2*
Max EVER angle (°)	*-8.0*	*-10.0*	*-11.0*	*-11.0*
Min EVER angle (°)	*-2.0*	*-1.0*	*-1.0*	*-1.0*

Table 6.33 describes the mean frontal plantar plane angle of the forefoot to rearfoot relationship using metatarsals 2-4 or 1-5 in feet classified with a forefoot valgus from static examination (Data set A). The Max/Min angle of EVER(°).

Contrary to the hypothesis, the calcaneus inverted (supinated) relative to the tibia during propulsion in most feet classified with a forefoot valgus (Table 6.35, Figures 6.29a-6.29b). On the right, the calcaneus was inverted relative to the tibia 1.8° (SEM =1.8), (p=0.05) more than feet classified with no forefoot deformity (from the 2-4 metatarsal assessment). However, Levene's test for equality of variances was significant (p = 0.04) for this comparison. This indicates that there is unequal variance between the groups. This could be attributed to the small numbers of feet in either classification, rather than an actual difference between the classification of feet.

On the left, in feet classified with a forefoot valgus there was a greater range of frontal plane motion (4.2° (SEM = 2.4), (p = 0.03)) of the midfoot relative to the calcaneus during propulsion, than feet classified with no forefoot deformity. In contrast, on the right the range of frontal plane motion of the midfoot relative to the calcaneus was comparable between both classifications of feet. A similar number of feet from both classifications inverted during this phase. For example, the midfoot inverted (supinated) relative to the calcaneus during propulsion in 84% of feet classified with a forefoot valgus, and 78% of feet classified with no forefoot deformity (for the 1-5 metatarsal assessment).

All r values indicate a low correlation between the frontal plantar plane angle of the forefoot to rearfoot relationship measured from static examination, and both gait parameters (left: r = <-0.339 (p = 0.257), right: r = <-0.144 (p = 0.410) (Table 6.36) Figures 6.29e-6.29f). The r and s values are higher for the 2-4 metatarsal assessment, than the 1-5 metatarsal assessment for both gait parameters.

Segment	Gait Parameter	Descriptive Analysis (+ve ROM INV)	2-4 metatarsal assessment				1-5 metatarsal assessment			
			Left		Right		Left		Right	
			No Forefoot deformity	Forefoot valgus	No forefoot deformity	Forefoot valgus	No forefoot deformity	Forefoot valgus	No forefoot deformity	Forefoot valgus
Calcaneus-Tibia		No. of feet (n)	#	n=13	*n=4*	*n=14*	*n=4*	*n=20*	*n=9*	*n=35*
	ROM during propulsion	Mean (°)		9.9	9.2	10.9	10.9	8.2	10.5	10.5
		SD (°)		*2.8*	*0.8*	*3.5*	*4.8*	*5.6*	*3.1*	*3.8*
		95% CI (°)		*8.2- 11.6*	*7.9- 10.6*	*8.9- 13.0*	*3.3- 18.6*	*5.6- 10.9*	*8.9- 13.0*	*9.2- 11.8*
		No. of feet INV ROM (n, %)		*n=13 (100%)*	*n=4 (100%)*	*n=14 (100%)*	*n=4 (100%)*	*n=18 (90%)*	*n=9 (100%)*	*n=35 (100%)*
		Max INV ROM (°)		*19.7*	*10*	*16.6*	*16.0*	*14.7*	*15.1*	*17.6*
		Min INV ROM (°)		*5.7*	*8.2*	*5.7*	*6.0*	*4.7*	*5.4*	*2.9*
		No. of feet EVER ROM (n,%)		*0*	*0*	*0*	*0*	*n=2 (10%)*	*0*	*0*
		Max EVER ROM (°)		*-*	*-*	*-*	*-*	*-7.7*	*-*	*-*
		Min EVER ROM (°)		*-*	*-*	*-*	*-*	*-4.2*	*-*	*-*
		No Forefoot Deformity v's Forefoot Valgus p			**0.05***		0.239		0.489	
Midfoot-Calcaneus	ROM during propulsion	Mean (°) **	#	-0.6	1.7	1.8	3.1	-1.1	1.8	2.4
		SD (°)		*4.7*	*3.5*	*3.2*	*4.7*	*4.2*	*2.7*	*2.7*
		95% CI (°)		*-3.4- 2.2*	*-3.9- 7.3*	*-0.2- 3.9*	*-4.3- 10.4*	*-3.1- 0.9*	*-0.3- 3.9*	*1.4- 3.4*
		No. of feet INV ROM (n, %)		*n=6 (46%)*	*n=3 (75%)*	*n=9 (75%)*	*n=3 (75%)*	*n=10 (50%)*	*n=7 (78%)*	*n=27 (84%)*
		Max INV ROM (°)		*6.6*	*5.3*	*5.2*	*6.5*	*3.7*	*4.9*	*5.3*
		Min INV ROM (°)		*2.5*	*2.3*	*1.1*	*4.5*	*1.3*	*1.2*	*1.1*
		No. of feet EVER ROM (n,%)		*n=7 (54%)*	*n=1(25%)*	*n=3 (25%)*	*n=1(25%)*	*n=10 (50%)*	*n=2 (22%)*	*n=5 (16%)*
		Max EVER ROM (°)		*-8.0*	*-3.2*	*-3.4*	*-3.8*	*-8.5*	*-3.5*	*-3.9*
		Min EVER ROM (°)		*-2.7*	*-*	*-2.6*	*-*	*-2.2*	*-0.9*	*-2.6*
		No forefoot deformity v's Forefoot Valgus p			0.478		**0.03**		0.161	

Table 6.34 describes the mean range of frontal plane motion of the calcaneus relative to the tibia and the midfoot relative to the calcaneus during propulsion in feet classified with a forefoot valgus, or no forefoot deformity with comparison between classifications of feet. The number of feet displaying range of INV/EVER (n, %). The Max/Min range of INV/EVER (°). #: Indicates in-sufficient numbers of feet for the No forefoot deformity classification (2-4 assessment). *Levene's test for equality of variances: Not assumed (p 0.04), in replacement the p value from the equal variances are not assumed independent t-test was used which has used a different degrees of freedom (15.9) for the calculation. **Right: Midfoot-Calc ROM during propulsion data missing from FF Valgus 2-4 examination (n=2/14) and FF Valgus 1-5 examination (n=3/35).

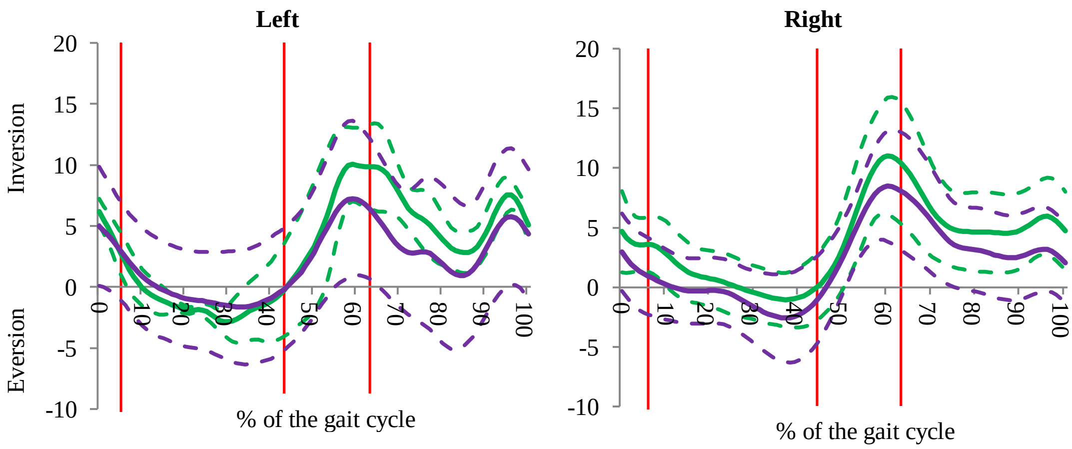


Figure 6.29a (left) and 6.29b (right): Frontal plane movement of the calcaneus relative to the tibia during the gait cycle. Green line: no forefoot deformity. Purple line: forefoot valgus from the 1-5 metatarsal assessment. Solid line represents mean, dashed lines represent standard deviation. Vertical red lines represent the timing of forefoot loading, heel lift and toe off.

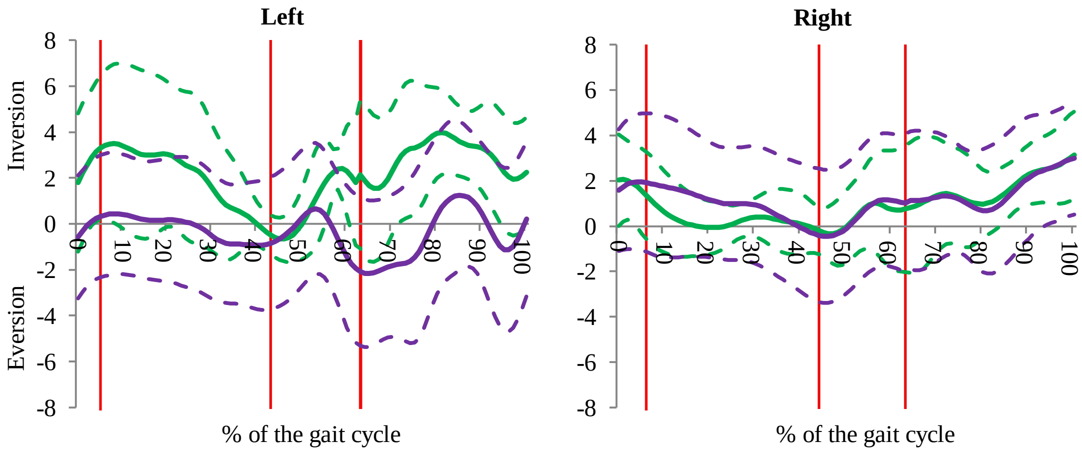
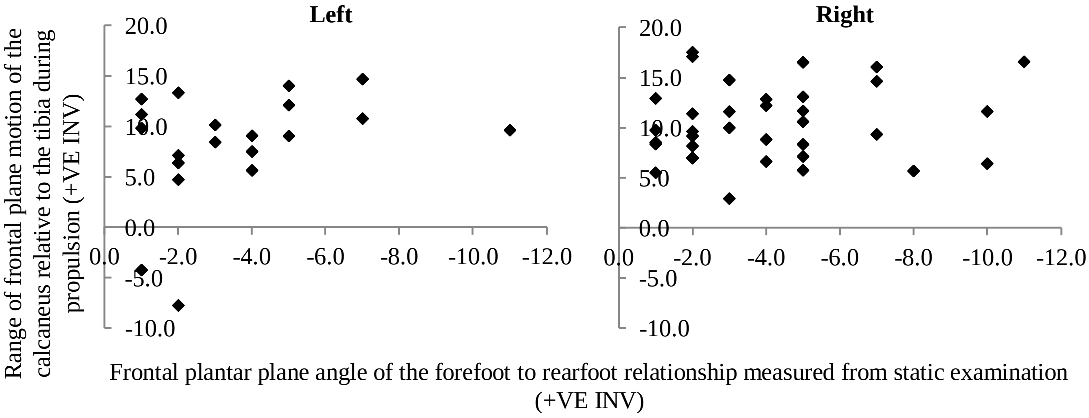


Figure 6.29c (left) and 6.29d (right): Frontal plane movement of the midfoot relative to the calcaneus during the gait cycle. Green line: no forefoot deformity. Purple line: forefoot valgus from the 1-5 metatarsal assessment. Solid line represents mean, dashed lines represent standard deviation. Vertical red lines represent the timing of forefoot loading, heel lift and toe off. (Similar plots were created for the 2-4 metatarsal assessment).

Segment	Gait Parameter	**Correlation (r/s (p))**			
		2-4 metatarsal assessment		**1-5 metatarsal assessment**	
		Left (n =13)	**Right(n=14)***	**Left (n= 20)**	**Right(n=35)***
Calcaneus-Tibia	ROM during propulsion	r = -0.339 (0.257)	r = -0.100 (0.733)	s = -0.286 (0.11)	r = 0.035 (0.915)

Table 6.35 presents the results of Pearson's and Spearman's correlations (r/s, (p)) between the frontal plantar plane angle of the forefoot to rearfoot relationship measured from static examination, and the range of frontal plane motion of the calcaneus relative to the tibia during propulsion in feet classified with a forefoot valgus. r: Pearson's correlation. s: Spearman's correlation.



Figures 6.29e (left) and 6.29f (right) presents a scatter plot of the correlation between the frontal plantar plane angle of the forefoot to rearfoot relationship measured from static examination, and the range of frontal plane motion of the calcaneus relative to the tibia during propulsion in feet classified with a forefoot valgus. (Similar plots were created for the 2-4 metatarsal assessment).

Discussion

The examination of the forefoot to rearfoot relationship was proposed by Root et al (1971, 1977), and is described by podiatrists in Chapter 4, Section 4.2 as an important examination of the foot. Some (Buchanan and Davis 2005, Donatelli et al 1999, Garbalosa et al 1994, McPoil et al 1988) have reported the incidence of a forefoot valgus deformity of the foot in asymptomatic participants. However, there are only very few investigations (Donatelli et al 1999, McPoil and Cornwall 1996b) that have reported the kinematic movement, or function of feet classified with this structural deformity of the forefoot during the stance phase of walking.

Root et al (1977) proposed that a foot classified with a forefoot valgus is predisposed to or will present with injury, most commonly to the first metatarsophalangeal joint. However, in this investigation and others (Buchanan and Davis 2005, Donatelli et al 1999, Garbalosa et al 1994, McPoil et al 1988) some feet were classified with a forefoot valgus deformity, and all investigations included only asymptomatic participants. This suggests that contrary to what Root et al (1977) proposed the angle of the forefoot to rearfoot relationship is not, and does not need to be in a neutral (0°) angle for a foot to be symptom free. There was no agreement between podiatrists in Chapter 4, Section 4.2 as to whether the 1-5 or 2-4 metatarsal assessment should be used. Buchanan and Davis (2005), Donatelli et al (1999), McPoil et al (1988) and Garbalosa et al (1994) all used the 1-5 metatarsal assessment method. However, Root et al (1971, 1977) suggested that including the first metatarsal into this measurement can result in the incorrect classification of the forefoot as valgus, because of a plantarflexed first ray deformity. In consideration of the high prevalence of a plantarflexed first ray deformity reported by this investigation (left: n=77 (76%), right: n=75 (78%)) the 2-4 metatarsal assessment of the forefoot was used as well as the 1-5 metatarsal assessment. Using the 2-4 metatarsal assessment, the number of feet classified with a forefoot valgus decreased from 20 to 13 feet on the left, and from 35 to 14 feet on the right.

The results from this investigation demonstrate that feet classified with a forefoot valgus do not function as Root et al (1977) proposed. There is little difference in the kinematic movement of feet classified with a forefoot valgus, or no forefoot deformity. In almost all feet classified with a forefoot valgus, or no forefoot deformity the calcaneus inverted relative to the tibia during propulsion. Therefore the subtalar joint did not pronate during this phase. The range of frontal plane motion of the calcaneus relative to the tibia is also similar for both classifications of feet using either assessment technique. The angle of the forefoot valgus deformity can also not infer the range of frontal plane motion of the calcaneus relative to the tibia. The results of correlations between these parameters indicate a weak or no relationship with $r = <-0.339$ ($p = 0.257$) on the left, $r = <-0.100$ ($p = 0.733$) on the right. Overall, this questions the use and clinical value of assessing the forefoot to rearfoot relationship.

According to Root et al (1971, 1977) the movement of the midtarsal joint during the gait cycle in the normal foot is dependent on the movement of the subtalar joint. The results from this investigation indicate that in most feet classified with a forefoot valgus the subtalar joint supinated during propulsion, therefore it would suggest that the midtarsal joint should pronate, and not supinate during propulsion. This would be representative of what Root et al (1977) proposed is the movement of the midtarsal joint in the normal foot. However, contrary to Root et al (1977) in the majority of feet classified with a forefoot valgus, or no forefoot deformity the midfoot inverted (supinated) relative to the calcaneus during propulsion. However, as similar to Leardini et al (2007) and DeMits et al (2012) there is some inter-participant variation in the movement of the midfoot during propulsion. This makes it difficult to assume inferences from solely using the mean value. For example, in feet classified with a forefoot valgus the mean values indicates eversion, except on the left only 50% of feet everted during this phase.

A limitation of this investigation is that the subtalar joint was not placed in a neutral position prior to the static examination measurement of the forefoot to rearfoot relationship. Instead the resting angle of the foot was used. This method was selected in reference to Garbalosa et al (1994), Elveru et al (1988), Diamond et al (1989), and Smith-Orrichio and Harris (1990) who reported difficulty in trying to place and maintain the subtalar joint in a neutral position when examining the foot non weight bearing.

A second limitation of this investigation again relates to the measurement of the forefoot to rearfoot relationship. To measure the angle of the forefoot to rearfoot relationship a photograph was taken of the plantar aspect of the foot. The measurements were then calculated from this. Agreeably, it would have been preferable to measure the forefoot to rearfoot relationship directly as used in Garbolosa et al (1994), Buchanan and Davis (2005) and McPoil et al (1988). However, all investigations, and even Root et al (1977) state that accurately conducting this examination is highly error prone due to the difficulty in holding the foot in the required position, and taking the measurement.

Overall, this hypothesis is rejected. This is because feet classified with a forefoot valgus do not function as Root et al (1977) proposed, and instead function very similar to how feet classified with no forefoot deformity function. The forefoot valgus angle cannot predict the range of frontal plane motion of the calcaneus relative to the tibia during the stance phase of walking.

6.5.10 Hypothesis 7.b - A foot classified with a forefoot varus deformity defined from static examination will pronate at the subtalar joint throughout the stance phase of the gait cycle, and the subtalar joint will be in a maximally pronated position during propulsion. This is compared to a normal foot which will pronate at the subtalar joint during the contact phase, and supinate at the subtalar joint during midstance and propulsion.

More feet were classified with a forefoot varus using the 2-4 metatarsal assessment (right: n=82), than the 1-5 metatarsal assessment (right: n=56) (Table 6.37).

Descriptive analysis (+ve angle INV)	Feet classified as forefoot varus			
	2-4 metatarsal assessment		1-5 metatarsal assessment	
	Left	Right	Left	Right
No. of feet (n)	n=86	*n=82*	*n=75*	*n=56*
Mean (°)	8.9	7.5	6.0	5.3
SD	*4.6*	*4.9*	*3.8*	*4*
95% CI (°)	*7.9- 9.8*	*6.4- 8.6*	*5.2- 6.9*	*4.2- 6.4*
Max INV angle (°)	*19.0*	*20.0*	*16.0*	*16.0*
Min INV angle (°)	*1.0*	*1.0*	*1.0*	*1.0*

Table 6.36 describes the mean frontal plantar plane angle of the forefoot assessed using metatarsals 1-5 or 2-4 measured relative to the rearfoot in feet classified with a forefoot varus from static examination (Data set A). The Max/Min angle of INV/ (°).

In agreement with the hypothesis, in the majority of feet classified with a forefoot varus deformity, or no forefoot deformity the calcaneus everted relative to the tibia during the contact phase (Table 6.38, Figures 6.30a and 6.30b). In feet classified with a forefoot varus, there was a greater range of frontal plane motion of the calcaneus relative to the tibia during the contact phase -1.2° (SEM = 0.9), ($p= 0.05$) (1-5 metatarsal assessment, left only) than feet classified with no forefoot deformity.

The calcaneus remained in an everted position during midstance, and then inverted during propulsion relative to the tibia in the majority of feet classified with a forefoot varus, or no forefoot deformity. This movement pattern of both classifications of feet is demonstrated in Figures 6.30a and 6.30b. The range of frontal plane motion of the calcaneus relative to the tibia during midstance, and propulsion was similar and not significantly different in feet classified with a forefoot varus or no forefoot deformity. Compared to feet classified with no forefoot deformity, in feet classified with a forefoot varus the peak angle of eversion of the calcaneus relative to the tibia was greater during midstance -2.3° (SEM = 1.), ($p = 0.02$), and propulsion -2.4° (SEM = 1.2), ($p = 0.02$) (1-5 metatarsal assessment, right only).

Overall, in very few feet was the peak angle of eversion greater during propulsion than during midstance. In 3/82 (2-4 metatarsal assessment), 7/86 (1-5 metatarsal assessment) feet on the left, and 3/82 (2-4 metatarsal assessment), 1/56 (1-5 metatarsal assessment) feet on the right classified with a forefoot varus the peak angle of calcaneal eversion relative to the tibia was greater during propulsion, than during midstance.

Segment	Gait Parameter	Descriptive Analysis (+ve angle/ ROM INV)	2-4 metatarsal assessment				1-5 metatarsal assessment			
			Left		Right		Left		Right	
			No forefoot deformity	Forefoot varus	No forefoot deformity	Forefoot varus	No forefoot deformity	Forefoot varus	No forefoot deformity	Forefoot varus
Calcaneus-Tibia	No. of feet (n)		*	n=86	n=4	n=82	n=4	n=75	n=9	n=56
	ROM during contact phase	Mean (°)		-2.2	-3.2	-1.7	-3.3	-2.1	0.9	-1.7
		SD (°)		*1.8*	*1.5*	*2.2*	*0.9*	*1.8*	*3.4*	*1.9*
		95% CI (°)		*-2.6- -1.8*	*-5.6- -0.9*	*-2.2- -1.2*	*-4.7- -1.9*	*-2.6- -1.7*	*-3.2- 1.3*	*-2.2- -1.1*
		No forefoot deformity v's forefoot Varus p			0.07		**0.05**		0.388	
	ROM during midstance	Mean (°)		-4.5	-3.4	-4.1	-2.5	-4.5	-5.5	-4.2
		SD (°)		*5.1*	*5.2*	*4.4*	*8.8*	*5.3*	*2.3*	*4.4*
		95% CI (°)		*-5.6- -3.4*	*-11.6- 4.9*	*-5.1- -3.2*	*-16.6- 11.5*	*-5.7- -3.3*	*-7.0- -3.9*	*-5.3- -2.9*
		No forefoot deformity v's forefoot Varus p			0.484		0.465		0.311	
	ROM during propulsion	Mean (°)		9.7	9.2	11.2	10.9	10.1	10.5	11.5
		SD (°)		*5.5*	*0.8*	*3.9*	*4.8*	*5.2*	*2.9*	*3.8*
		95% CI (°)		*8.5- 10.9*	*7.9- 10.6*	*10.3- 12.0*	*3.3- 18.6*	*8.8- 11.3*	*8.5- 12.5*	*10.5- 12.6*
		No forefoot deformity v's forefoot varus p			0.08		0.386		0.181	
	Peak angle of EVER during midstance	Mean (°)		-4.2	-3.4	-3.8	-3.7	-4.3	-1.7	-4.1
		SD (°)		3.3	3.3	3.3	0.9	3.1	2.8	3.3
		95% CI (°)		-4.9- -3.4	-4.7- -1.9	-4.5- -3.1	-5.3- -2.1	-4.9- -3.6	-3.6- 0.11	-4.9- -3.2
		No forefoot v's forefoot varus p			0.403		0.421		**0.02**	
	Peak angle of EVER during propulsion	Mean (°)		-1.6	0.8	-0.9	0.8	-1.6	1.2	-1.2
		SD (°)		*4.0*	*1.2*	*3.6*	*5.0*	*3.8*	*3.2*	*3.6*
		95% CI (°)		*-2.5- 0.7*	*-1.2- 2.7*	*-1.7- -0.2*	*-7.3- 8.7*	*-2.4- 0.7*	*-0.9- 3.3*	*-2.2- -0.3*
		No forefoot deformity v's forefoot varus p			0.173		0.299		**0.02**	

Table 6.37 describes the mean angle and range of frontal plane motion of the calcaneus relative to the tibia during the contact, midstance and propulsion phases and the peak angle of eversion during propulsion in feet classified with a forefoot varus or no forefoot deformity with comparison (p) between classifications of feet. * Indicates in-sufficient numbers of feet for the no forefoot deformity classification (2-4 assessment).

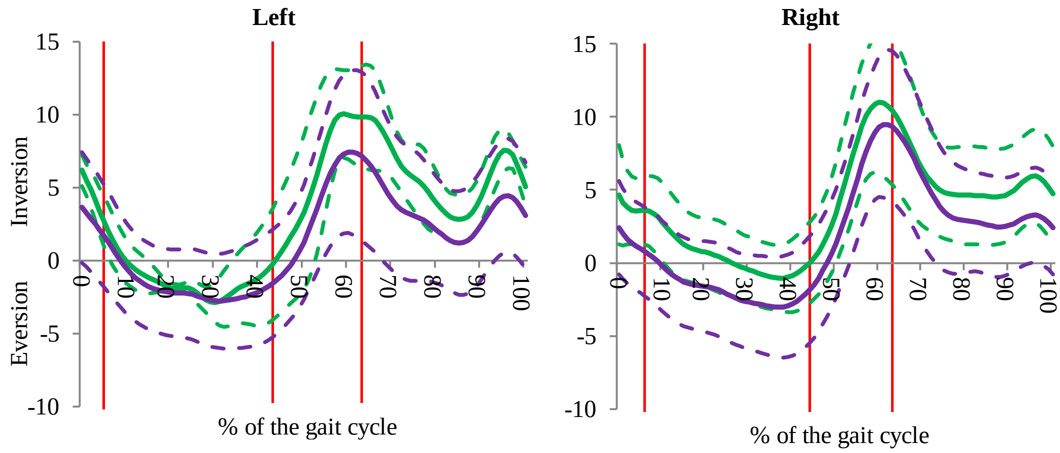
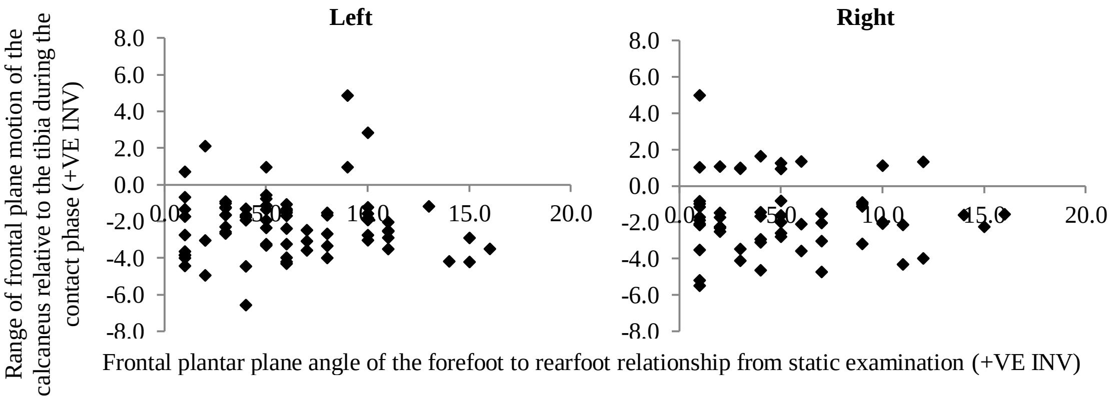


Figure 6.30a (left) and 6.30b (right): Frontal plane movement of the midfoot relative to the calcaneus during the gait cycle. Green line: no forefoot deformity. Purple line: forefoot varus from the 1-5 metatarsal assessment. Solid line represents mean, dashed lines represent standard deviation. Vertical red lines represent the timing of forefoot loading, heel lift and toe off. (Similar plots were created for the 2-4 metatarsal assessment).

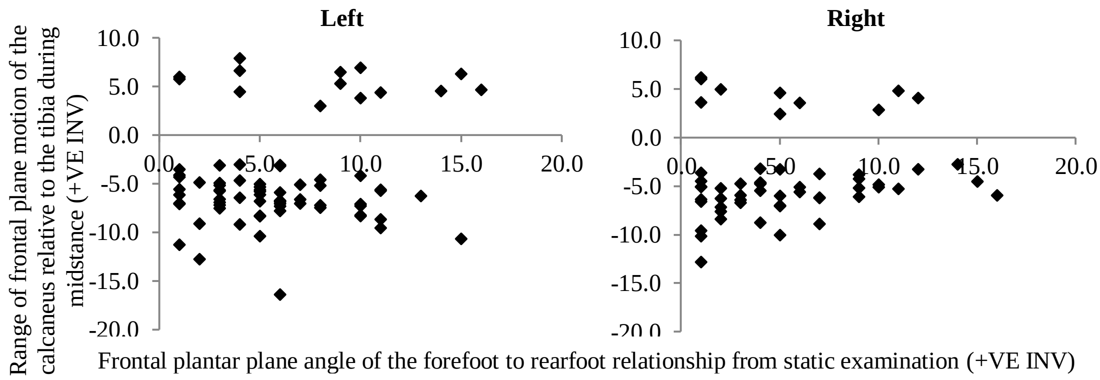
All s values indicate no to low correlation between the frontal plane angle of the forefoot to rearfoot relationship, and the range of frontal plane motion of the calcaneus relative to the tibia during stance phase i(left: s = <0.218 (p = 0.03), right: s = < 0.264 (p = 0.03)) Table 6.39, Figures 6.30c-6.30g. The s values were marginally higher for the 1-5 metatarsal than the 2-4 metatarsal assessment.

Correlation (s (p))					
Segment	**Gait parameter**	**Static Examination (Data set A)**			
		2-4 metatarsal assessment		**1-5 metatarsal assessment**	
		Left (n=86)	**Right (n=82)**	**Left (n=75)**	**Right (n=56)**
Calcaneus-Tibia	ROM during contact phase	-0.03 (0.410)	0.05 (0.323)	-0.06 (0.293)	-0.01 (0.465)
	ROM during midstance phase	0.162 (0.07)	0.102 (0.181)	0.01 (0.455)	0.215 (0.05)
	ROM during propulsion	0.07 (0.275)	-0.106 (0.171)	0.218 (0.03)	-0.214 (0.06)

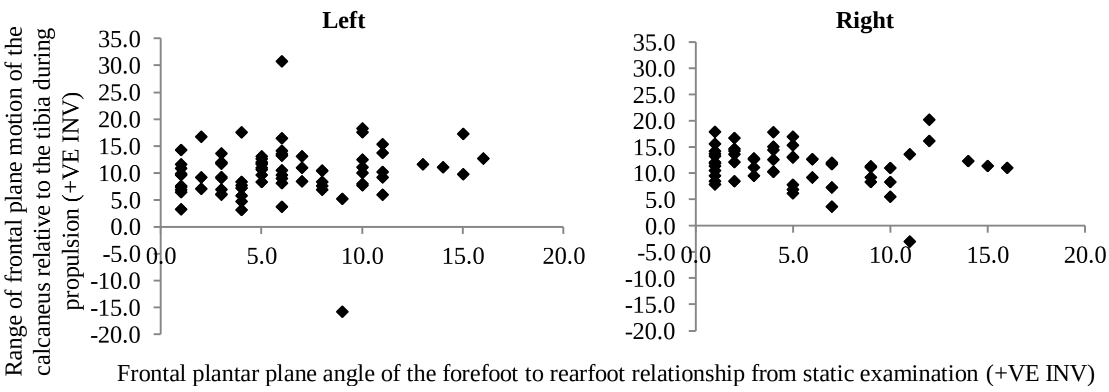
Table 6.38 presents the results of Spearman's correlations (s, (p)) between the frontal plantar plane angle of the forefoot to rearfoot relationship from static examination (Data set A), and the range of frontal plane motion of the calcaneus relative to the tibia during the contact, midstance and propulsion phases in feet classified with a forefoot varus. s: Spearman's correlation



Figures 6.30c (left) and 6.30d (right) presents a scatter plot of the correlation between the frontal plantar plane angle of the forefoot to rearfoot relationship measured from static examination, and the range of frontal plane motion of the calcaneus relative to the tibia during the contact phase in feet classified with a forefoot varus. (Similar plots were created for the 2-4 metatarsal assessment).



Figures 6.30e (left) and 6.30f (right) presents a scatter plot of the correlation between the frontal plantar plane angle of the forefoot to rearfoot relationship measured from static examination, and the range of frontal plane motion of the calcaneus relative to the tibia during midstance in feet classified with a forefoot varus. (Similar plots were created for the 2-4 metatarsal assessment).



Figures 6.30g (left) and 6.30h (right) presents a scatter plot of the correlation between the frontal plantar plane angle of the forefoot to rearfoot relationship measured from static examination, and the range of frontal plane motion of the calcaneus relative to the tibia during propulsion in feet classified with a forefoot varus. (Similar plots were created for the 2-4 metatarsal assessment).

Discussion

The examination of the forefoot to rearfoot relationship was proposed by Root et al (1971, 1977), and is described by podiatrists in Chapter 4, Section 4.2 as an important examination of the foot. Some (Buchanan and Davis 2005, Donatelli et al 1999, Garbalosa et al 1994, McPoil et al 1988) have reported the incidence of a forefoot varus deformity of the foot in asymptomatic participants. However, there are only very few investigations (Donatelli et al 1999, McPoil and Cornwall 1996b) that have reported the kinematic movement, or function of feet classified with these structural deformities of the forefoot during the stance phase of walking.

Root et al (1977) proposed that a foot classified with a forefoot varus is predisposed to, or will present with injury, most commonly to the first metatarsophalangeal joint. However in this investigation and others (Buchanan and Davis 2005, Donatelli et al 1999, Garbalosa et al 1994, McPoil et al 1988) the majority of the feet examined were classified with a forefoot varus deformity and all investigations included only asymptomatic participants. This suggests that contrary to what Root et al (1977) proposed the angle of the forefoot to rearfoot relationship is not, and does not need to be in a neutral (0°) angle for a foot to be symptom free.

There was no agreement between podiatrists in Chapter 4, Section 4.2 as to whether the 1-5 or 2-4 metatarsal assessment should be used. Buchanan and Davis (2005), Donatelli et al (1999), McPoil et al (1988) and Garbalosa et al (1994) all used the 1-5 metatarsal assessment method. However, Root et al (1971, 1977) suggested that including the first metatarsal into this measurement can result in the incorrect classification of the forefoot as varus because of a dorsiflexed first ray deformity. Although, in this investigation very few feet were classified with a dorsiflexed first ray (left: n=6 (6%), right: n=7 (7%)), there was a considerable number of feet classified with a plantarflexed first ray deformity (left: n=77 (76%), right: n=75 (78%)). Therefore, the 2-4 metatarsal assessment of the forefoot was used as well as the 1-5 metatarsal assessment. The number of feet classified with a forefoot varus increased from 56 to 82 feet on the right, and from 75 to 85 feet on the left.

The results from this investigation demonstrate that feet classified with a forefoot varus do not function as Root et al (1977) proposed. The kinematic movement of feet classified with a forefoot varus is very similar to feet classified with no forefoot deformity, across all phases of the stance phase of the gait cycle. During the contact and midstance phases in feet classified with a forefoot varus, or no forefoot deformity the calcaneus everted relative to the tibia, and then inverted during propulsion. This is supported by the results from Hunt et al (2001a) and others (Leardini et al 2007, Cornwall and McPoil 1999a, Kitaoka et al 2006, Simon et al 2006, Rattanaprasert et al 1999, Arndt et al 2004 and Lundgren et al 2007). They reported a similar movement pattern, and a similar range of frontal plane motion of the calcaneus relative to the tibia, or talus during each phase of the gait cycle. The angle of the forefoot varus deformity can also not infer the range of frontal plane motion of the calcaneus relative to the tibia during any phases of the stance phase of the gait cycle. The results of correlations between these parameters indicate a lack of a relationship with $s = 0.218$ ($p = 0.03$) on the left and $s = 0.264$ ($p = 0.03$) on the right. During the contact phase, in feet classified with a forefoot varus or no forefoot deformity the calcaneus everted relative to the tibia. Root et al (1977) implied that feet classified with a forefoot varus will have to evert more during this phase to achieve a plantigrade contact with the supporting surface, because the forefoot is in an inverted position. However, the results of this investigation demonstrate that in feet classified with a forefoot varus the range of motion was smaller, and not as everted (<-1.2°, p = 0.05) than feet classified with no forefoot deformity. Root et al (1977) proposed that feet classified with a forefoot varus, are abnormal and will present or are pre-disposed to injury. However all participants included in this, and these investigations (Leardini et al 2007, Cornwall and McPoil 1999a, Kitaoka et al 2006, Simon et al 2006, Rattanaprasert et al 1999, Arndt et al 2004 and Lundgren et al 2007) are asymptomatic. This adds further evidence to question whether the examination of the forefoot to rearfoot relationship can infer a pre-disposition to injury.

The results from this investigation demonstrate that contrary to Root et al (1977) in feet classified with a forefoot varus the peak angle of calcaneal eversion relative to the tibia occurred during midstance, and not during propulsion. This similar to feet classified with no forefoot deformity. For example, using the 1-5 metatarsal method the peak angle of eversion during midstance was -2.7° (SEM =0.6), (p = <0.001) on the left, and -2.8° (SEM = 0.7), (p = <0.001) on the right greater than during propulsion. This is supported by many other investigations (Leardini et al 2007, Cornwall and McPoil 1999a, Kitaoka et al 2006, Simon et al 2006, Rattanaprasert et al 1999, Hunt et al 2001a, Arndt et al 2004, Lundgren et al 2007). They reported that contrary to Root et al (1977) the peak angle of eversion of the calcaneus relative to the tibia occurred during midstance, and not at forefoot loading or during propulsion.

The two limitations of the method of examination of the forefoot to rearfoot relationship discussed in Hypothesis 7.a should also be considered when evaluating the results from this hypothesis.

Overall, this hypothesis is rejected. This is because feet classified with a forefoot varus do not function as Root et al (1977) proposed and instead function very similar to how feet classified with no forefoot deformity function. The forefoot varus angle cannot predict the range of frontal plane motion of the calcaneus relative to the tibia during the stance phase of walking.

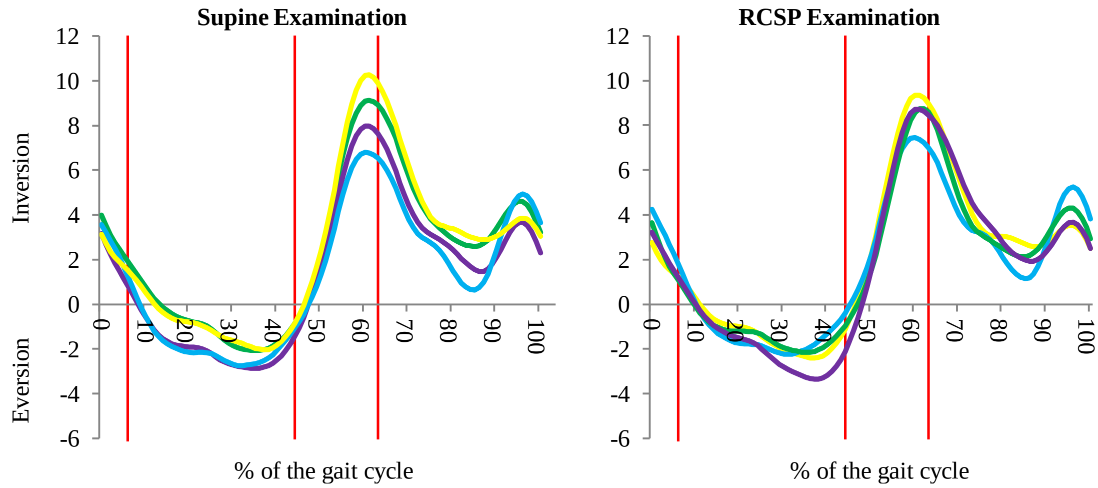
6.5.11 Hypothesis 8: The longer limb will demonstrate different re-supination characteristics at the subtalar joint during the phase of midstance, and propulsion compared to those with equal limb length.

In individuals classified with a limb length discrepancy, the peak angle of calcaneal eversion relative to the tibia was greater in the short limb than those of equal limb length during midstance. It was -0.9° (SEM=0.6), (p=0.05) for the supine examination, and -1.3° (SEM=0.8), (p=0.05) for the RCSP examination greater than those of equal limb length (p = >0.169). However, Figures 6.31a and 6.31b indicate that the frontal plane movement of the calcaneus relative to the tibia throughout the gait cycle is very similar in individuals classified with, or without a limb length discrepancy from either examination.

The peak angle of calcaneal eversion relative to the tibia during propulsion was similar in both limbs in individuals classified with, or without a limb length discrepancy.

Gait Parameter	**Descriptive Analysis (+ve angle INV)**	**Supine**				**RCSP**			
		No LLD (Left)	**No LLD (Right)**	**LLD (Long Leg)**	**LLD (Short Leg)**	**No LLD (Left)**	**No LLD (Right)**	**LLD (Long Leg)**	**LLD (Short Leg)**
	No. of feet (n)	n=34	n=34	n=59	n=59	n=52	n=52	n=40	n=40
Peak angle of EVER during midstance	Mean (°)	-4.3	-3.5	-3.2	-4.2	-3.7	-3.6	-3.3	-4.5
	SD (°)	*3.8*	*3.1*	*2.9*	*3.3*	*3.3*	*2.9*	*3.2*	*3.7*
	95% CI (°)	*-5.6- -2.9*	*-4.5- -2.4*	*-3.9- -2.5*	*-5.1- -3.4*	*-4.7- -2.8*	*-4.5- -2.8*	*-4.3- -2.3*	*-5.7- -3.4*
	No. of feet INV angle (n, %)	*n=2 (6%)*	*n=6 (18%)*	*n=6 (10%)*	*n=5 (8%)*	*n=4 (8%)*	*n=5 (10%)*	*n=5 (12%)*	*n= 4 (10%)*
	Max INV angle (°)	*5.4*	*2.4*	*4.2*	*2.3*	*3.4*	*2.4*	*4.2*	*2.3*
	Min INV angle (°)	*0.02*	*0.04*	*0.1*	*0.1*	*0.1*	*0.04*	*0.4*	*0.1*
	No. of feet EVER angle (n, %)	*n=32 (94%)*	*n=28 (82%)*	*n=53 (90%)*	*n=54 (92%)*	*n=48 (92%)*	*n=47 (90%)*	*n=35 (88%)*	*n=36 (90%)*
	Max EVER angle (°)	*-13.0*	*-11.0*	*-10.4*	*15.4*	*-13.1*	*-11.0*	*-10.4*	*-15.4*
	Min EVER angle (°)	*-0.5*	*-0.9*	*-0.9*	*-0.4*	*-0.4*	*-0.4*	*-0.1*	*-0.3*
	Long Leg (or Left Leg) v's Short Leg (or Right leg) p	0.169		**0.05**		0.349		**0.05**	
Peak angle of EVER during propulsion	Mean (°)	-1.3	-0.4	-0.6	-1.5	-0.7	-0.7	-0.8	-2.0
	SD (°)	*4.7*	*3.2*	*3.2*	*3.8*	*4.1*	*3.3*	*3.3*	*4.1*
	95% CI (°)	*-2.9- 0.4*	*-1.5- 0.8*	*-1.4- 0.2*	*-2.5- -0.6*	*-1.8- 0.5*	*-1.6- 0.2*	*-1.9- 0.3*	*-3.3- 0.7*
	No. of feet INV angle (n, %)	*n=9 (26%)*	*n=15 (44%)*	*n=32 (54%)*	*n=22 (37%)*	*n=22 (42%)*	*n=20 (38%)*	*n=16 (40%)*	*n=14 (35%)*
	Max INV angle (°)	*8.4*	*6.1*	*8.1*	*5.6*	*8.4*	*6.1*	*8.1*	*5.6*
	Min INV angle (°)	*0.3*	*0.1*	*0.1*	*0.2*	*0.3*	*0.1*	*0.1*	*0.2*
	No. of feet EVER angle (n, %)	*n=25 (74%)*	*n=19 (56%)*	*n=27 (46%)*	*n=37 (63%)*	*n=30 (58%)*	*n=32 (62%)*	*n=24 (60%)*	*n=26 (65%)*
	Max EVER angle(°)	*-11.9*	*-8.2*	*-6.8*	*-14.4*	*-11.9*	*-8.3*	*-6.8*	*-14.4*
	Min EVER angle (°)	*-0.1*	*-0.6*	*-0.3*	*-0.2*	*-0.1*	*-0.4*	*-0.3*	*-0.2*
	Long Leg (or Left Leg) v's Short Leg (or Right leg) p	0.183		0.165		0.435		0.112	

Table 6.39 describes the mean peak angle of eversion of the calcaneus relative to the tibia during midstance, and propulsion in individuals classified with, or without a limb length discrepancy from two static methods of limb length examination (Data set A). Table presents comparison (p) between classification of long (or right) versus short (or left) limbs. The number of feet displaying angle of INV/EVER (n, %). The Max/Min angle of INV/EVER (°). LLD: limb length discrepancy. No LLD: No limb length discrepancy.



Figures 6.31a (Supine) and 6.31b (RCSP): Frontal plane movement of the calcaneus relative to the tibia during the gait cycle. Green line: long limb. Purple line: Short limb. Blue line: No LLA (left foot). Yellow line: No LLA (right foot). Solid line represents mean. Vertical red lines represent the mean timing of forefoot loading, heel lift and toe off for all right and left feet.

Discussion

The examination of limb length was proposed by Root et al (1977), and is described by podiatrists in Chapter 4, Section 4.1 as an important static examination of the lower limb. The examination of limb length was also the only biomechanical examination that podiatrists in Chapter 4, Section 4.1 routinely conducted that was external to the foot.

Root et al (1977) proposed and all podiatrists in Chapter 4, Section 4.1 stated that any difference in limb length was classified as abnormal. However, the results from this investigation, Pappas and Nehume (1979), Friberg (1983) and descriptions from Brady et al (2003) indicate that a difference in limb length is both common and not always a cause of symptoms.

All participants examined in this investigation were asymptomatic. From the Supine examination 63% of participants, and from the RCSP examination 53% of participants were classified with a limb length discrepancy. The majority of participants were classified with a limb length discrepancy less than 5mm. Only 5 from 59 participants from the supine examination, and 4 from 40 participants from the RCSP examination were classified with a leg length discrepancy greater than 10mm. This is in agreement with Friberg (1983) who suggested that 50% of an asymptomatic population will have a limb length discrepancy. Pappas and Nehume (1979) proposed that a difference in limb length of up to 11mm is not a cause of symptoms. Although, Gross (1983) and McCaw and Bates (1991) reported that individuals can be symptom free even with a difference in limb length of up to 30mm. Overall, this indicates that for an individual to be symptom free they do not have to have limbs of equal length.

Brady et al (2003) described how there is little consensus on how the body compensates for a limb length discrepancy during walking and whether it is the limb classified as long or short that will modify its function to accommodate. Root et al (1977) stated that a limb length discrepancy is a cause of abnormal pronation of the subtalar joint during midstance, and propulsion. However, they provided no description as to whether it is the long or short limb that will demonstrate this proposed abnormal movement. Michaud (1997) suggested that the foot of the limb classified as short may pronate excessively in an attempt to achieve flat plantigrade contact with the floor. This is indicated by the results of this investigation as the peak angle of calcaneal eversion relative to the tibia is greater in the limb classified as short than the long. However, this difference appears to be relatively minimal (mean difference: $<1.3°$, ($p = 0.05$)) and not a cause of symptoms as all participants were asymptomatic. In contrast, McCaw and Bates (1991) proposed that the foot of the long limb will be in a more pronated position than the foot of the short limb. This would not be supported by the results presented by this investigation. Although, McCaw and Bates (1991) suggested that there will be a smaller range of motion in the foot of the longer limb as it has already reached its maximum amount of rotation available.

A limitation of this investigation is that it has only used indirect methods of limb length examination. However, this method was selected because of the superior reliability and smaller error reported by Woerman and Binder-Macleod (1984), Jonson and Gross (1997) and described by Brady et al (2003). All podiatrists in Chapter 4, Section 4.2 stated that they only used indirect methods of examination.

A second limitation of this investigation is that for this hypothesis only the movement of the calcaneus in the frontal plane relative to the tibia was measured. Further research could investigate the effect a difference in limb length has on other joints within the foot.

Overall, this hypothesis is accepted. This is because there is a difference in the frontal plane angle of the calcaneus relative to the tibia during midstance in individual classified with a limb length discrepancy, and there is not in individuals with no limb length discrepancy. As only 4 individuals had a limb length discrepancy greater than 10mm, it suggests that in consideration of the large number of participants included in this investigation, large limb length differences are not common in an asymptomatic population.

6.6 Overall Discussion

The results from this investigation question the Root et al (1977) description of normal and abnormal kinematics of the foot. First,, in agreement with many others, the Root et al (1977) description of the movement, and function of the foot during the gait cycle is incorrect. Second, in agreement with prior research, the measurements obtained from the Root et al (1971, 1977) static biomechanical assessment of the foot cannot predict the function of the foot during the gait cycle.

6.6.1 The Root et al (1977) description of the movement of the normal foot during the gait cycle, does not concur with that of feet classified as asymptomatic

Root et al (1977) proposed that the normal foot will demonstrate specific mechanical characteristics during the gait cycle. They proposed that the joints within the foot will demonstrate a specific angle at different stages, and specific ranges of motion during the phases of the gait cycle. However, no feet in this investigation matched this description, and yet all are asymptomatic and therefore can be considered normal. Other concepts within the Root et al model are also not supported by this investigation. For example, the foot does not represent a mobile adaptor during the contact phase or a rigid lever during midstance and propulsion. This conclusion is supported by many (McPoil and Cornwall 1994, McPoil and Cornwall 1996a, Leardini et al 2007, Hunt et al 2001a, Cornwall and McPoil 1999a, Nester 2009, Rattanaprasert et al 1999, Kitaoka et al 2006, Lundgren et al 2007, Arndt et al 2004, Jenkyn and Nicol 2007, DeMits et al 2012). They reported similar movement patterns of the foot during the gait cycle in feet that are asymptomatic.

The large number of participants included in this investigation allows us to describe the differences between people in the movement of the foot during walking with greater confidence than previous research. A key difficulty identified in Chapter 2 was that although there are many investigations (Leardini et al 2007, Hunt et al 2001a, Rattanaprasert et al 1999, Kitaoka et al 2006, Lundgren et al 2007, Arndt et al 2004, DeMits et al 2012, Jenkyn and Nicol 2007, Carson et al 2001, MacWilliams et al 2003, Moseley et al 1996) that have described the kinematics of the foot during the gait cycle, the small cohort sizes mean that they might not offer a more definite description of foot kinematics.

One of the most probable reasons why it is not possible to describe specific movements of how the foot moves during walking is because of the large inter-participant variation in the how the joints of the foot move. There was variation in the angle, and range, and the direction of motion, for all inter-segmental combinations and for each phase of the gait cycle. This suggests that contrary to Root et al (1977) it is not possible, or appropriate to stipulate specific movements are required for a asymptomatic foot. Therefore, in agreement with Astrom and Arvidson (1995), Razeghi and Batt (2002), and Nester (2009) this investigation recommends that the term "normal," should be replaced with "asymptomatic". This is because it can allow for the normal variation between people to be accommodated into models of foot function. It presupposes that absence, or presence of symptoms has greater clinical importance than whether a foot demonstrates specific movement patterns assumed to be optimal in terms of efficiency (Nester et al 2009).

In this investigation, the inter-participant variation was described using various methods, including basic statistical analysis such as the standard deviation and 95% confidence intervals. The number and percentage of feet displaying a specific pattern, and the maximum and minimum value from within the cohort for each gait parameter tested for each hypothesis was also reported. This provided additional information to indicate whether there is a consistent pattern of movement across the sample of participants. In some instances a similar number of feet were moving in either direction of motion in the same plane (i.e. inversion and eversion). Therefore, the mean value can in some instances provide a potentially misleading representation of the range of motion or angle between two segments.

The foot model used in this investigation provided detailed information about the kinematics of the foot during the gait cycle. The complex design which includes six segments has medial and lateral forefoot regions, and a midfoot region. In conjunction with the results from others (DeMits et al 2012, MacWilliams et al 2003, Jenkyn and Nicol 2007, Lundgren et al 2007, Nester et al 2006, Wolf et al 2008, Lundberg et al 1989a, Lundberg et al 1989b, Lundberg et al 1989c), it appears to provide important information about the movement of these regions of the foot during walking, which are largely neglected by Root et al (1977). For example, the range of motion of the lateral forefoot relative to the midfoot was sometimes comparable to that of the calcaneus relative to the tibia. This suggests that this region of the foot plays an important contribution to foot function. However, Root et al (1977) provided no description of the function of the fifth ray during walking. Therefore their description is clearly incomplete, and too crude to represent foot movements effectively. This helps to emphasise that it is just as important to measure, and understand the movement of the joints within the mid, and forefoot as well as the rearfoot.

A limitation of this and other (Leardini et al 2007, Hunt et al 2001a, Rattanaprasert et al 1999, Kitaoka et al 2006, DeMits et al 2012, Jenkyn and Nicol 2007, Carson et al 2001, MacWilliams et al 2003, Moseley et al 1996) investigations is that the techniques used cannot measure the exact movement of the joints of the foot. This is because skin based methods can only attempt to try and represent the movement of the bones of the foot. This means it is sometimes difficult to compare experimental data directly to Root et al (1971, 1977) proposed model of foot function. The most pertinent example of this is the description of the movement of the calcaneus relative to the tibia. Root et al used frontal plane movement between these bones to represent the subtalar joint, and sagittal plane motion to represent the ankle. Agreeably, this technique lacks the integrity or accuracy of methods using intra-cortical bone pins. However, the method used could be regarded as comparable to the Root et al (1971, 1977) description of the movement of the subtalar joint in the frontal plane. Root et al (1971, 1977) proposed that when weight bearing only the calcaneus will move in the frontal plane, and the talus will move in the sagittal and transverse planes upon the talus. Therefore, as the calcaneus is modelled as the rigid segment that is measured relative to the tibia, it appears to provide a good representation of what Root et al (1977) described. Root et al (1977) described the rotation of the midtarsal joint around proposed oblique and longitudinal axes. There is no description of the movement of the individual bones of the midtarsal joint. Instead, the cuboid and navicular are described as one functional unit moving relative to the talus and calcaneus. This is somewhat similar to the methods employed in this investigation, and used by others as the movement of the navicular and cuboid were described together as one rigid segment. However, the movements of the bones within the midfoot were described relative to each other, not around the two assumed co-existent axes of rotation described by Root et al. There is arguably an insurmountable amount of evidence (Tweed et al 2008, Nester et al 2001, Nester and

Findlow 2006 Vogler and Bojson-Moller 2000, Huson 1991, Huson 2000) which demonstrates that there cannot be two axes of rotation at the midtarsal joint. This supports the experimental and modelling methods used in this investigation and others (Hunt et al 2001, Leardini et a 2007, DeMits et al 2012, MacWilliams et al 2003, Jenkyn and Nicol 2007, Kitaoka et al 2006, Simon et al 2006, Lundgren et al 2007, Nester et al 2006). Trying to measure movement using Root et al (1971, 1977) two axes model would be impossible (Nester et al 2006).

There are some limitations of this investigation that apply to the general methodology of this investigation. First, each participant completed in total 24 walking trials, which in overall may induce some fatigue. However, all participants included in this investigation are asymptomatic, and each was asked to grade their activity level between 1 (not active) and 5 (very active). The mean result for the cohort is 3.2 (SD = 0.9). This suggests that most participate in regular exercise, and therefore could tolerate the walking required for this study. Such difficulties are more important when designing studies for participants who are older, injured or suffering from a chronic disease.

The second limitation is that only one gait cycle was recorded per walking trial. Although, each walking trial contained at least 3 gait cycles before and after contacting the force plate. It is therefore assumed that each gait cycle is similar within each walking trial. However, the inter-walking trial variation reported by Lundgren et al (2007) suggests that there could be some variation between walking trials. There was no attempt to control the speed of walking of each participant either as the aim was to represent the normal walking pattern of each individual as best possible.

The third limitation is that kinetic data was collected simultaneously with the kinematic data using a force plate placed embedded within the floor. Participants may have tried to aim their foot at the force plate which may not be conducive to their normal walking pattern. Participants were advised to not look at the floor when they were walking and were provided with time to practice so that they became accustomed to walking in the gait laboratory. However, this is a problem faced by most investigations measuring kinematics and kinetics of human walking.

6.6.2 The measurements obtained from a static based biomechanical assessment of the foot cannot predict the movement of the foot during the gait cycle

In Chapter 4, Section 4.2, podiatrists stated that the examinations included in Data Set A, Chapter 5, Section 5.3 are integral components of their routine biomechanical assessment of the foot protocol. They stated that the measurements obtained would be used for three key reasons. First, to classify the foot with or without a structural deformity, second, to infer how that foot will function during walking, and third, for the development of a prescription for the construction of an orthoses device. However, the results from this investigation, which is in agreement within others, strongly indicate that these examinations are not reliable or valid.

The results from Research Question 2 demonstrate that in agreement with some (Hamill et al 1989, Cornwall and McPoil 1999b, McPoil and Cornwall 1994, McPoil and Cornwall 1996a, Pierrynowski and Smith 1996, Nawoczenski et al 1999, Van Gheluwe et al 2006) the measurements or classification of feet obtained from any of the examinations included in Data Set A, Chapter 5, Section 5.3 cannot predict the function of the foot during walking. They do not provide an accurate representation of the movement, or function of the joint, or region of the foot examined during the gait cycle. There were large differences between the measurements obtained from all of the Root et al (1971, 1977) assessment protocol, and the angle or movement of the same joint or region of the foot during the gait cycle.

The measurements from these static examinations were considerably larger, and therefore over-estimated the range of motion, or angle of a joint that would be reached during the respective stage or phase of the gait cycle. For example, Root et al (1977) proposed that the range of dorsiflexion at the first metatarsophalangeal joint must be at least 65° in a static examination, and it will be dorsiflexed to this at toe off. Agreeably, in this investigation and in agreement with the surrounding literature (Halstead and Redmond 2006, Halstead et al 2005, Nawoczenski et al 1999, Van Gheluwe et al 2006, Hopson et al 1995) in the majority of the feet the range of dorsiflexion at the first metatarsophalangeal joint measured in a static non-weight bearing examination was greater than 65°. However, in contrast to this, and other (Halstead and Redmond 2006, Halstead et al 2005, Nawoczenski et al 1999, Van Gheluwe et al 2006, Carson et al 2001, MacWilliams et al 2003, Simon et al 2006) investigations report that at toe off the hallux was dorsiflexed relative to the medial forefoot in nearly all feet between only 35°-50°. This suggests that when the foot is weight bearing, the joints of the foot move differently, and are more constrained due to the forces from body weight and the supporting surface. There are similar difficulties with the Root et al (1971, 1977) description of how feet classified with a structural deformity will function. Root et al (1977) proposed that a foot classified with any of these structural deformities will be pre-disposed to, or present with injury. However, a considerable number of feet were classified with at least one of these structural deformities in the sample of symptom free fete investigated here.

This is the case for a large number of other investigations too (McPoil et al 1988, Garbalosa et al 1994, Buchanan and Davis 2005, Donatelli et al 1999, Halstead et al 2005, Hamill et al 1989, Cornwall and McPoil 1999b). The majority of feet classified with any of these structural deformities do not function as Root et al (1977) proposed. They instead function very similar to how feet classified with no structural deformities function. As these deformities do not appear to be a cause of injury, it would question the appropriateness of describing them as "deformities," as this implies that a foot classified with these would be pre-disposed to injury and there is no evidence of this.

Overall, it appears to be the static nature of these examinations which is the cause of the lack of agreement between the static measurements, and the movement of the foot during the gait cycle. Walking is a dynamic activity. Therefore, an assessment of foot function needs to capture the changes in the foot and leg due to body weight, interaction with the supporting surface and the other movements in the body. By using a dynamic assessment protocol these factors can be accounted for, whereas in a static based assessment many of these factors are absent. In Chapter 4, Section 4.2 podiatrists stated that their understanding of what they perceived represented the movement of the normal foot during walking is based primarily on the description by Root et al (1977). However, the results from Research Question 1 in this investigation demonstrate that Root et al (1977) description of the function of the foot during the gait cycle is incorrect. Therefore, an overhaul of the current biomechanical assessment protocol of the foot and leg is required in podiatry, moving from static to dynamic measures of foot function.

Root et al (1971, 1977) proposed that the measurements obtained from following their assessment protocol are used in the development of a prescription for the construction of an orthotic device. However, these measurements are not an accurate representation of how the foot moves during walking. This questions the clinical effectiveness of using them, and may explain the reported (Hawke et al 2008, Landorf and Keenan 2006) poor efficacy of orthotic devices in treating soft tissue injuries of the foot and leg. Further investigations are required to better understand the mechanisms of how orthotic devices work, and how to as effectively as possible construct the appropriate orthotic prescription plan for individual patients.

A limitation of this and other (McPoil et al 1988, Garbalosa et al 1994, Buchanan and Davis 2005, Donatelli et al 1999, Halstead et al 2005, Hamill et al 1989, Cornwall and McPoil 1999b, McCaw and Bates 1991, Woerman and Binder-Macleod 1984, Pappas and Nehume 1979, Friberg 1983) investigations is that they are not longitudinal. Therefore, they cannot confirm that the participants included in them will remain symptom free. There is also some evidence (Turner et al 2007, Barton et al 2011, McClay 1999, Levinger et al 2010) to suggest that the kinematic movement of the foot in the symptom free foot is different in some respects, but differences are small, and unsystematic across participants when compared to the symptomatic foot. This contrasts with Root et al (1971, 1977) systematic classification of strict boundaries between normal and abnormal feet.

6.6.3 Clinical Implications

This investigation sought to critique, and evaluate the current model used in podiatry to apply biomechanical principles to the diagnosis of foot problems and their management with orthotics. This included the protocol for conducting a static based biomechanical assessment of the foot, and the description of foot function and movement during the gait cycle. The descriptions by Root et al (1971, 1977) transformed podiatric biomechanical clinical practice. It provided an assessment protocol, description of the function of the foot during the gait cycle, and a treatment rationale via use of functional foot orthosis. This highlighted the potential role of the podiatrist, and has been described by some (McPoil and Hunt 1995, Kirby 2000) to have contributed to the heightened status of podiatry. It helped to improve its perceived role in the management of musculoskeletal disorders and injury.

There were three key potential clinical implications from this investigation. First, the protocol for conducting a static based biomechanical assessment of the foot needs to be replaced with a dynamic based assessment. Second, there should be a re-appraisal of what clinicians perceive is normal or abnormal. Third, an evaluation of the current methods used for developing a prescription for a functional foot orthoses.

One of the key findings from the literature review in Chapter 2, was that most recent investigations had not determined what examinations podiatrists were currently using. This was important since the method of examination may have changed from the original description provided by Root et al (1971, 1977). Therefore, the results of a Delphi technique investigation described in Chapter 4, Section 4.2 are able to present a more up to date and accurate representation of the protocol used by podiatrists. This was very important in ensuring that the research of this investigation has direct relevance to current methods used by podiatrists. As all podiatrists included in Chapter 4, Section 4.2 routinely attend national workshop or seminar days, and are involved with a regional based biomechanical forum group it would suggest that the basis to their examination protocol is similar nationwide.

The reliability of an examination is used to determine if the measurements obtained are of any clinical value (Bruton et al 2000). The poor intra and inter-assessor reliability of most of the examinations included within Data Set A, Chapter 5, Section 5.3 suggest it is not possible to accurately determine if a treatment plan is working. This is because repeat examinations after the initial consolation are more than likely going to be different due to the error of the examination, and are therefore not a true reflection of the changes from the treatment provided.

The clinical value of these examinations is further questioned as none of the examinations used in Data set A, Chapter 5, Section 5.3 could accurately predict, or even infer the function or movement of the foot during walking. In consideration of the absolute importance of evidence based practice in healthcare (Ghali et al 1999, Hay et al 2008), these results would suggest that the current methods used by podiatrists to assess the biomechanical function of the foot are not reliable, or valid. Therefore, this investigation suggests that the current static based protocol used when conducting a biomechanical assessment of the foot needs to be replaced with a dynamic assessment protocol. However, implementing these new ideas and methods into podiatry will require careful planning. Previous models (McPoil and Hunt 1995, Dananandberg 2000, Kirby 1989) had largely failed to be incorporated into current clinical practice. Hay et al (2008) suggested that a possible reason for the poor adoption of new research is that clinicians favour their own, or a colleague's experience, rather than using evidence based literature. Hay et al (2008) reported that the main barrier to why clinicians seemed unwilling or unsure about new research was that they found it difficult to understand. It did not provide enough emphasis on how the information could be converted into a format that could be used by them in clinical practice.

However, to implement such changes will require further investigation to determine the necessary methods, what technologies to use, what can be feasibly used within the confines of routine clinical practice.

Further investigations are required to determine the necessary methods, the technologies to use, and what can be feasibly used within the confines of routine clinical practice. In order to successfully implement a new assessment protocol it will be necessary to take into account some of the problems faced by clinicians, particularly for those working in the NHS. Factors such as time constraints and the need for cost effectiveness have to be given prime consideration (Dixon and Glennerster 1995, Eve et al 1996). Agreeably, the Root et al (1971, 1977) static based biomechanical assessment protocol of the foot is easy to conduct in the confines of the clinic, and very little expensive equipment is required. There is also no, or little additional data processing or analysis required. In contrast, the technologies used by specialist human movement gait laboratories as detailed by this investigation are very expensive, time consuming, and require a large space for a gait laboratory set up. It is unlikely that for what would be classified as routine biomechanical musculoskeletal injuries, or complaints of the foot and lower limb such as plantar fasciitis or achilles tendinopathy would warrant such an elaborate set up. Agreeably, in cases of serious neurological (for example stroke or cerebral palsy), or rheumatological disease (for example rheumatoid arthritis or osteoarthritis) there is a definite need for a more in-depth gait analysis assessment. This additional expensive assessment approach might be more easily justified if it can help tailor expensive interventions such as surgery more appropriately (Helliwell et al 2007, Gage 1992).

It is not only a change from a static to a dynamic based assessment that is required. The results from this investigation strongly suggest that a re-appraisal in how clinicians perceive what is normal, or abnormal is very much required. There is significant evidence provided by this investigation and many others (Nester et al 2009, Astrom and Arvidson 1995, Hunt et al 2001a, Buchanan and Davis 2005, Razeghi and Batt 2002) to support a change from defining abnormality of the foot based on structural alignment, or mechanical characteristics and instead more on symptomology. Nester (2009) suggested that the results from more recent cadaver (Nester et al 2006), and intra-cortical bone pin (Lundgren et al 2007, Arndt et al 2004, Wolf et al 2008) investigations demonstrate the considerable range of motion, and functional capabilities of individual feet. Therefore, a patient specific symptom based approach would be the optimum method of assessment. Clinicians should instead base their assessment on the quality, velocity, and timing of motion at the different joints of the foot. There would also be an allowance for a wider variation in the measurements that can be classified as representative of symptom free function.

A change in the assessment protocol, and how to measure the biomechanical function and movement of the foot will have direct ramifications for orthotic practice. This is because they may not necessarily provide the numerical measurements currently used for orthotic prescription. Therefore, with the development of a new assessment protocol, further work will be required to determine what information, and how it should be used to construct foot orthoses. The results from this investigation also suggest that the current casting techniques need to be evaluated. Root et al (1971) also advocated the placement of the subtalar joint into a neutral position. However, the results from this investigation demonstrate that the placement of the subtalar joint into a neutral position is not reliable, or a position used during static standing or walking.

Overall, the results from this investigation demonstrate that there is a definite need for a change in the current practices within podiatric biomechanics. This should ensure the protocols used are based on evidence based medicine, and provide an improvement in patient outcomes.

6.6.4 Future Work

The results from this investigation question the current basis to podiatric biomechanics. In response to this, and the absolute importance of ensuring that methods used in clinical practice are supported by valid evidence based research, an overhaul of the current basis to podiatric biomechanics is required. This will hopefully lead to the development of a new clinical model. Whilst it is not within the purpose of this investigation to develop a new clinical model, it can instead suggest areas of future work which can involve using data from this investigation, and other resources.

Presented within this section are six proposed investigations that describe a brief methodology, the importance of this future work, and the clinical implications they could have.

Development of a new clinical model for the biomechanical assessment of, and the treatment of biomechanical disorders of the foot

For the development of a new clinical model that is to be used for conducting a biomechanical assessment of the foot, and the treatment of musculoskeletal disorders or injuries of the foot and leg a series of additional investigations to supplement the results of this investigation will be required. These will include a. Development of a protocol for conducting a dynamic based biomechanical assessment of the foot, b. What measurements, if any should be used for diagnosis of the presenting problem and c. Determine what information should be used for the construction of foot orthoses and treatment plans.

The results from this, and other (Kitaoka et al 2006, Lundgren et al 2007, Hunt et al 2001A, Leardini et al 2007, Nester et al 2006, Nester et al 2007, Simon et al 2006, Carson et al 2001, MacWilliams et al 2003) investigations provide a detailed description about the biomechanical function of the foot. However, this information needs to be converted into a more clinically orientated model. This will ensure a clinician can use the description to assess a patient walking, and determine how best to treat the presenting problem. This was a definite weakness of McPoil and Hunt (1995), Kirby (1989), and Dananberg (2000) as they failed to provide a new assessment protocol, or treatment plan.

Improving the integration of research into clinical practice

There is a definite need for the development of strategies that will aid the integration of research into podiatric biomechanics, so to challenge and change if required current practices. This will involve: a. Provide significant evidence based research through peer reviewed publication of the results from this investigation. It will be important to ensure that these are written so that clinicians can interpret the results, and use them towards their clinical practice, b. Integration of these new concepts into under and post graduate education and c. To work with clinicians, and understand the constraints placed upon their current practice, such as time and financial constraints.

Using assessment protocols to educate patients

With the proposed changes in how the current biomechanical assessment of the foot should be conducted, it also provides an ideal opportunity to integrate more patient education based methods. Deakin and Whitham (2009), Deakin et al (2006), and Skou et al (2012) adopted patient education based treatment based regimes and all described considerable improvements in patient compliance. Thus, the patients reported that they are more effectively managing their condition. This indicates that these techniques could be very useful when conducting a biomechanical assessment, and administering some treatment regimes. This will include developing the most effective method for explaining the assessment protocol and diagnosis to the patient. By providing the patient with a greater understanding of their presenting condition or injury, and how their foot is implicated in their condition, it should improve their compliance. For example, a common treatment regime provided by podiatrists and other allied health professionals are different stretching exercises. However, the effectiveness of this regime is dependent on the diligence of the patient to conduct the required exercises. By educating the patient and effectively empowering them to understand the importance of the proposed treatment regime, it should improve their adherence to it and enhance treatment outcomes.

Provide a complete description of the biomechanical function of the foot, leg, and lower limb during the gait cycle in asymptomatic individuals.

One of the initial aims of this investigation was to provide a more accurate description of the asymptomatic foot. This should provide a better comparison to the diseased, or pathological foot. This description can then be integrated into clinical practice, and podiatry education. In conjunction with the kinematic data of the tibia, and foot previously described, this investigation also measured the kinematic motion of the femur and pelvis during the gait cycle. Therefore, it can provide an overall description of the kinematics of the lower limb during the gait cycle.

This investigation also simultaneously collected other data with the kinematic data. kKnetic data using an AMTI force plate, plantar pressure data using an Novel EMED-X-E Plantar Pressure System (Novel, Munich, Germany), and electromyographical data using Noraxon Telemyo G2 wireless electromyography system (Noraxon, Scottsdale, Arizona). This recorded the activity of the tibialis anterior, medial and lateral gastrocnemius and soleus. Future work could include combining this information together with other additional literature. Such as those that have measured the activity of other muscles of the foot and leg, and other equipment including ultrasonography to create a complete description of the biomechanical function of the foot and leg during the gait cycle in asymptomatic individuals. This can then be compared to the injured or diseased foot. Some smaller investigations (Turner et al 2007, Halstead et al 2005, Helliwell et al 2007, Sawacha et al 2012) using a limited number of participants have combined some of these different types of data. However, none as yet offer the large number of participants included in this investigation, or the complex design of the foot model used with this additional data.

Use of the Salford foot model to measure the kinematic motion of the diseased or injured foot

The Salford foot model has only been used to measure the kinematics of asymptomatic feet. Future work could involve using this foot model, and adapting so it can measure the kinematics of the foot in the elderly, or young, the diabetic, arthritic or neurological disorder affected foot. The results can then be compared to this investigation to determine if there are any differences, or similarities between the function of the foot in these patient groups, and the asymptomatic foot. This could provide useful insights into how the function of the foot changes due to age, disease or injury.

Understanding the inter-dependent function of the foot

The inter-dependent function of the joints of the foot play an integral role in its function during the gait cycle. Some (Wolf et al 2008, Pohl et al 2006, Eslami et al 2007, Huson 1991 and Dierks and Davis 2007) have described this as coupling mechanisms. These investigations (Wolf et al 2008, Pohl et al 2006, Eslami et al 2007, Huson 1991 and Dierks and Davis 2007) have attempted to describe how there are complex kinematic chains of motion within the foot. These are proposed to be able to aid the ability of the foot to provide adaptability with the supporting surface, and support of body weight.

There are various mathematical, and statistical techniques for exploring the coupling mechanisms between the joints of the foot. Some of which are presented by Wolf et al (2008), Pohl et al (2006), Eslami et al (2007) and Dierks and Davis (2004). In consideration of the number of participants included in this investigation, and the complex foot model design, the data from this investigation could provide useful insights into the inter-dependent function of the foot. Future work will have to firstly establish with statisticians the most appropriate method to investigate coupling between, and within the joints measured.

6.7 Conclusions

The current basis to podiatric biomechanics is the descriptions by Root et al (1971, 1977). This included a description of the function of the foot during the gait cycle, and a protocol for conducting a static based biomechanical assessment of the foot. However, the results from this investigation, and many others demonstrate that the Root et al (1977) descriptions of what is proposed to represent the normal foot are incorrect, and there is not a normal foot. The considerable inter-participant variation in how the joints of the foot move during walking suggest that it is not possible to describe specific angles, or range of motion to define asymptomatic foot function.

The examinations within the Root et al (1971, 1977) biomechanical assessment protocol are not reliable, and nor can they predict or even infer how the foot assessed will move during walking. Almost all feet classified with a structural deformity following the Root et al (1971m 1977) guidelines did not function as they proposed. However, they were also all asymptomatic. This questions the proposed relationship between these foot deformities, and the development of injury. Therefore, the results from this investigation suggest that the current Root et al (1971, 1977) static based protocol for the biomechanical assessment of the foot needs to be replaced with a dynamic based assessment. This will provide a better representation of the function of the foot during walking. It will incorporate new information about how the joints of the foot function during walking and it must allow for the inter-participant variation in how the joints within the foot move during walking. It will highlight how it is not possible for all feet to function the same, and for the assessment to be more based on symptomology and specific to that patient, rather than the mechanical characteristics of a foot.

APPENDICES

A.1: Investigation 1

An investigation into the different biomechanical examination techniques used by podiatric practitioners in clinical practice

A.1.1 University of Salford Research Ethics Panel (REP) reference: REP07/106

A.1.2 Participant information sheet

Professor Christopher Nester
BSc (Hon) PhD

Director, Centre for Rehabilitation and Human Performance Research

The University of Salford
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Salford, Greater Manchester
M6 6PU United Kingdom

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4 November 2008

Dear Podiatry colleague,

It is my pleasure to invite you to attend a special study day which is being held as part of a research project related to Podiatry practice. PhD candidate Hannah Jarvis will be hosting a study day to discuss the biomechanical examination techniques used by Podiatrists in clinical practice. The day will involve use of the “Delphi Technique” which has been widely used to derive consensus amongst groups of people (such as practitioners) through a process of questionnaires and group debate. We hope the day will prove interesting, challenges and fun.

During the morning you will be required to complete a questionnaire which captures your use of biomechanical examination techniques of the foot and leg. The responses will be discussed as a group in an attempt to derive a consensus on what are the most important examination techniques in biomechanics Podiatry practice. These examination techniques will then be used in a project that hopes to explore the relationship between clinical examination and foot motion, pressure and muscle activity during walking. Your thoughts and opinions are critical to the research being meaningful for future clinical practice and education of future Podiatry graduates. In the afternoon we will provide an interactive tutorial in “Advanced clinical gait analysis” where you will be able to take part in some gait analysis data collection and we will endeavour to answer your questions about the project and our gait facilities.

Please be assured that the information you provide will be kept strictly confidential. We will provide you with a certificate of attendance and provide an opportunity for reflective review, which can contribute to your CPD targets. A free buffet lunch and tea/coffee will be provided. If you would like further information and/or agree to take part, please contact Hannah directly via Email: H.L.Jarvis1@pgr.salford.ac.uk or Tel: 07866 033704.

We look forward to hearing from you.

Best wishes

Professor Christopher Nester

Director,

Centre for Rehabilitation and Human Performance Research

Institute for Health and Social Care Research, University of Salford, UK

A.1.3 Consent form

SALFORD RESEARCH
CONSENT FORM

Title of Project: An investigation into the different biomechanical examination techniques used by Podiatric practitioners in clinical practice.

Name of Researcher: Hannah Jarvis

Please initial box

1. I confirm that I have read and understand the information sheet dated..................... (version...................) 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 members of the University of Salford research staff/student who are working on the project will only look at images of my walking. I give permission for these individuals to have access to this data. ☐

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

Name of subject	Date	Signature
Name of Person taking consent	Date	Signature
Researcher	Date	Signature

A.1.4 Questionnaire

This presents the questionnaire used for the Delphi technique investigation described in Chapter 4.

"An investigation into the biomechanical examination techniques used by podiatrists in clinical practice."

Please answer the following questions, indicating how you would perform your biomechanical examination of the foot, leg and lower leg during clinical practice.

Unless otherwise stated please circle Yes or No or the appropriate answer.

Answer all questions anonymously and do no place any form of identification on the questionnaire.

No information will be shared with any third parties.

This is an investigation into what biomechanical examination techniques podiatrists use, not an assessment of your skills and practice.

Section A

This section will investigate your use of different examination techniques for assessing the foot and ankle of a patient requiring a biomechanical examination.

1. a.i. Do you measure Neutral calcaneal stance position (NCSP)? *Yes/No*

a.ii. If you have answered yes to question 1.a.i, how do you measure NCSP?

- Tractograph *Yes/No*
- Goniometer *Yes/No*
- Estimate *Yes/No*
- Other, please state……………………………………………………………

a.iii. How often do you use this examination technique on patients requiring a biomechanical examination? Please circle the appropriate statement

- Never
- Some of the time
- Most of the time
- All of the time

b.i. Do you measure Relaxed calcaneal stance position (RCSP)? *Yes/No*

b.ii If you have answered Yes, to question 1.b.i, How do you measure RCSP?

- Tractograph *Yes/No*
- Goniometer *Yes/No*
- Estimate *Yes/No*

- Other, please state …………………………………………………

b.iii. How often do you use this examination technique on patients requiring a biomechanical examination? Please circle the appropriate statement

- Never
- Some of the time
- Most of the time
- All of the time

c. If you have answered Yes to questions 1.a.i and 1.b.i., do you draw a heel bisection line on the posterior aspect of the calcaneus when performing this assessment? *Yes/No*

d. Do you compare the results of RCSP and NCSP and use this as a measure towards:

d.i. Defining a treatment rationale? *Yes/No*

d.ii. Assessment of foot type? *Yes/No*

2.a.i. Do you measure the "forefoot to rearfoot relationship?" ***Yes/No***

If you have answered yes to question 2.a.i., please answer the following questions. If you have answered No, please proceed to question 3.

Do you assess the patient:

a.ii. Prone *Yes/No*

a.iii. Supine *Yes/No*

b.i. In what planes of motion do you measure the "forefoot to rearfoot relationship?"

b.ii. How do you determine the forefoot relationship in the frontal plane?

- The middle three metatarsals of the forefoot? *Yes/No*
- All five metatarsals of the forefoot? *Yes/No*

c. What classification do you use to measure the "forefoot to rearfoot relationship" in the frontal plane?

- Classify position (e.g forefoot is parallel to rearfoot / or everted /inverted) *Yes/No*

- Measure forefoot to rearfoot relationship (e.g 4º Forefoot varus) *Yes/No*

d. How often do you use this examination technique? Please circle the appropriate statement.

- Never
- Some of the time
- Most of the time
- All of the time

3.a.i. Do you measure the range of motion at the ankle joint? *Yes/No*

If you have answered yes to question 3.a.i, please answer the following questions. If you have answered No, please proceed to question 4.a.i.

Do you measure the range of motion at the ankle joint:

a.ii. With the knee flexed *Yes/No*

a.iii. With the knee extended *Yes/No*

Do you measure:

- The total range of motion at the ankle joint? (plantarflexion and dorsiflexion combined) *Yes/No*

- The range and maximal amount of ankle joint dorsiflexion only? *Yes/No*

Other, please state ……………………………………………………………………

b.i. How do you measure the range of motion at the ankle joint?

- Tractograph *Yes/No*
- Goniometer? *Yes/No*
- Estimate? *Yes/No*

- Other device, please state………………………………………………

b.ii. How often do you use this examination technique on patients requiring a biomechanical examination? Please circle the appropriate statement.

- Never
- Some of the time
- Most of the time
- All of the time

4.a.i. Do you measure the range of motion at the subtalar joint? *Yes/No*

If you have answered yes to question 4.a.i, please answer the following questions, if you have answered No, please proceed to question 5.

Do you assess the patient:

a.ii. Prone *Yes/No*

a.iii. Supine *Yes/No*

a.iv. How often do you use this examination technique? Please circle the appropriate statement

- Never
- Some of the time
- Most of the time
- All of the time

b.i. Do you establish a subtalar joint neutral position (non-weight bearing) for examining the subtalar joint range of motion? *Yes/No*

b.ii. If you have answered Yes to question 4.b.i, do you palpate the surrounding anatomy of the subtalar joint and move the foot to obtain a neutral position? *Yes/No*

b.iii. Do you assess the direction of motion? (i.e in what plane is motion more evident.) *Yes/No* c.i. Do you use the Kirby method (“Rotational equilibrium across the subtalar joint axis”) to establish the position of the subtalar joint axis? *Yes/No*

c.ii. Do you establish the “pitch” of the subtalar joint axis in the sagittal plane? *Yes/No*

5.a.i. Do you measure the range of motion at the midtarsal joint? *Yes/No*

If you have answered yes to questions 5.a.i, please answer the following questions, if you have answered No, please proceed to question 6.

a.ii. How often do you use this examination technique? Please circle the appropriate statement

- Never
- Some of the time
- Most of the time
- All of the time

b.i. Do you measure the range of motion of the longitudinal axis of the midtarsal joint? *Yes/No*

b.ii. How do you measure the range of motion of the longitudinal axis of the midtarsal joint?

- Tractograph *Yes/No*
- Goniometer? *Yes/No*
- Estimate? *Yes/No*
- Other device, please state……………………………………………………

b.iii. Do you measure the range of motion of the oblique axis of the midtarsal joint? *Yes/No*

b.iv. How do you measure the range of motion of the longitudinal axis of the midtarsal joint?

- Goniometer? *Yes/No*
- Estimate? *Yes/No*
- Tractograph *Yes/No*
- Other device, please state ……………………………………………………

c. Do you assess the direction of motion? (i.e in what plane is motion more evident.) *Yes/No*

6.a.i. Do you measure the range of motion at the first ray? *Yes/No*

If you have answered yes to questions 6.a.i, please answer the following questions, if you have answered No, please proceed to question 7.

a.ii. How often do you use this examination procedure?

Please circle the appropriate statement

- Never
- Some of the time
- Most of the time
- All of the time

b.i. In what planes of motion do you measure the motion of the 1st ray?

b.ii. How do you quantify this range of motion in the sagittal plane (i.e Dorsiflexion/Plantarflexion)?

- State in "mm" the range of motion? *Yes/No*
- Classify it as rigid/flexible/normal? *Yes/No*

Other, please state ………………………………………………………………

c. Do you assess the position of the 1st ray? (e.g Determining if it is either plantarflexed/dorsiflexed/ parallel to the transverse plane of the second metatarsal) *Yes/No*

7.a.i. Do you measure the range of motion at the 1st metatarsophalangeal joint? *Yes/No*

If you have answered yes to questions 7.a.i, please answer the following questions, if you have answered No, please proceed to question 8.

Do you measure:

b.i. The total range of motion at the 1st metatarsophalangeal joint (dorsiflexion and plantarflexion combined)? *Yes/No* b.ii. The range and maximal amount of dorsiflexion at the 1st metatarsophalangeal joint? *Yes/No*

b.iii. How do you measure the range of motion at the 1st metatarsophalangeal joint?

- Tractograph *Yes/No*
- Goniometer? *Yes/No*
- Estimate *Yes/No*
- Other device, please state………………………………………………….

b.iv. How often do you use this measurements? Please circle the appropriate statement.

- Never
- Some of the time
- Most of the time
- All of the time

c.i. Do you use "Jack's test" for assessing the integrity of "The Windlass Mechanism"? *Yes/No*

(Jack's test: Patient is standing/weight bearing and the hallux is dorsiflexed, the change in the height of the medial longitudinal arch is recorded).

c.ii. How often do you use this measurement? Please circle the appropriate statement.

- Never
- Some of the time
- Most of the time
- All of the time

8. a. Do you use the Foot Posture Index? *Yes/No*

If you have answered yes to question 8.a, please answer the following questions. If you have answered no, please proceed to question 9.a.

b.i. Do you use the 8 point Foot Posture Index? *Yes/No* b.ii. Do you use the 6 point Foot Posture Index? *Yes/No*

c. Why do you use the Foot Posture Index?

c.i. To aid orthotic design and monitor the affect of the orthoses on foot type? *Yes/No*

c.ii. Record a validated measure of foot posture? *Yes/No*

9.a. Do you use the Foot Health status questionnaire? *Yes/No*

If you have answered yes to question 9.a, please answer the following questions, if you have answered No, please proceed to **Section B**, question 1.a.

b. Do you use the Foot Health status questionnaire to monitor treatment success? *Yes/No*

c. Do you use it to measure patient perception of their baseline health status? *Yes/N*

d. Other, please state ……………………………………………………………….

Section B.

This section will focus on your assessment of the leg and lower limb.

1.a. Do you measure and assess the lower limb? *Yes/No*

If you have answered yes to questions 1.a, please answer the following questions, if you have answered No, please proceed to **Section C**.

b. How do you measure for a possible limb length discrepancy?

- Tape measure *Yes/No*
- Palpation of bony landmarks *Yes/No*
- Estimation *Yes/No*
- Other, please state…………………………………………………………………..

c.i. Do you measure for an anatomical leg length difference? *Yes/No*

How do you measure for an anatomical leg length discrepancy?

- Anterior superior iliac spine to medial mallelous? *Yes/No*

- Posterior superior iliac spine to medial mallelous*? Yes/No*

Other, please state……………….…………………………………………….

d.i. Do you measure for a functional leg length discrepancy? *Yes/No*

How do you measure for a functional leg length discrepancy?

d.ii. Sternum to medial malleolus? *Yes/No*

d.ii. Umbilicus to medial malleolus? *Yes/No*

Other, please state ………………………………………………………….

e. On measuring a limb length discrepancy, how do you record the data?

- To the absolute mm/cm *Yes/No*

- A range in mm/cm (e.g 1-3cm) *Yes/No*

Other, please state…………………………………………………

f. How often do you use this examination technique? Please circle the appropriate statement.

- Never
- Some of the time
- Most of the time
- All of the time

g. Do you also measure?

- Internal/external Hip rotation? *Yes/ No*

- The “Q” angle? *Yes/No*

Other, please state………………………………………………………………….

Section C.

This section will discuss gait analysis.

1.a. Do you use gait analysis in your biomechanical examination of a patient in clinical practice?

Yes/No

If you have answered yes to question **Section C**.1.a, please answer the following questions, if you have answered No, please proceed to question 2.

b. Do you assess:

- The foot *Yes/No*
- The Ankle *Yes/No*
- The Knee *Yes/No*
- The Hip *Yes/No*
- The Upper body *Yes/No*

2.a. Do you have access to and use video/motion capture gait analysis? Yes/No

b. If you have answered yes to questions 2.a, what software do you use?

…...……………………………………………………………………………………………

c. How do you interpret/utilise the results from this analysis?

- To aid orthotic design and monitor the affect of orthoses on foot type? *Yes/No*

- Assess foot and/or lower limb movement? *Yes/No*

Other, please state…………………………………………………………………….

de. Do you think having access to this software enhances your examination and treatment plan?

Yes/No

3.a.i. Do you have access to Pressure plate equipment for gait analysis? *Yes/NO*

a.ii. If you have answered yes to question 3.a.i, what equipment/manufacturer do you use?

…………..………………………………………………………………………

b. How do you interpret/utilise the results from this analysis?

- To aid orthotic design and monitor affect of the orthoses on foot type? *Yes/No*

- Record a validated measure of foot pressure distribution? *Yes/No*

Other, please state……………………………………………………………

c. Do you think having access to this software enhances your examination and treatment plan?

Yes/No

4.a.i. Do you have access to Force plate equipment for gait analysis? *Yes/No*

a.ii. If you have answered yes to question 4.e.i, what equipment do you use?

…………...………………………………………………………………………

b. How do you interpret/utilise the results from this analysis?

- To aid orthotic design and monitor affect of orthoses on foot type? *Yes/No*

- Record a validated measure of force and calculate moments at joints? *Yes/No*

Other, please state………………………………………………………………...

c. Do you think having access to this software enhances your examination and treatment plan?

Yes/No

5. Please identify 5 key events (e.g Position of heel at initial contact) of the gait cycle that you would analyse when conducting a clinical gait analysis assessment.

1.
2.
3.

4.

5.

6. Please state any other biomechanical assessment you would use?

……………………………………………………………………………………………………
……………………………………………………………………………………………………

7. Additional comments:

……………………………………………………………………………………………………
……………………………………………………………………………………………………

A.2 Inter-reliability study day assessing the biomechanical examination protocol used by Podiatrists in clinical practice

A.2.1 University of Salford Research Ethics Panel (REP) reference: REP09/070

A.2.2 Information sheet for Assessors

You are being invited to take part in a research study. Before you decide whether to participate it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Please ask if there is anything that is not clear or if you would like more information.

Background to the study
From our previous meeting on the 7th January 2009, a consensus was agreed between all on what biomechanical examination procedures are used by Podiatrists in clinical practice, I now want to extend this further and invite you to attend a:

"Inter-reliability study day assessing the biomechanical examination protocol used by Podiatrists in clinical practice."

This will again form part of the preliminary research for my PhD.

Do you have to take part?
No. It is up to you to decide whether or not to take part. You are under no obligation.

Why you have been chosen?
We wish to recruit the same people that were used in the previous Delphi Technique study day and your expertise and knowledge from a clinical angle is most valuable.

What will happen to me if I take part?

The plan is firstly for all assessments to the demonstrated and explained so that all are coherent with what we want assessed, then all assessors (Podiatrists) will individually perform the specified biomechanical assessment of each subject once and record the results. All information will be completed and stored anonymously.
Please be ensured that this is an investigation into the reliability of these assessments not an individual assessment of you.

What are the possible disadvantages and risks of taking part?

This study is very low risk, it is what you use in your clinical practice and will be performed in a clinical environment.

What are the possible benefits of taking part?

This should provide a nice continuation from your previous help with the Delphi Technique study day.

What if there is a problem?

If you have concern about any aspect of the study the researcher (Hannah Jarvis) will do her best to answer any problems. Please contact her on H.L.Jarvis@pgr.salford.ac.uk, 07866 033704

What will happen if I do not want to participate in this study?

You can withdraw from the study at any time without giving a reason. Any data which has been collected data will be deleted.

Will my taking part in the study be kept confidential?

Yes. Any information obtained in connection with this study will be treated as privileged and confidential. All information will be kept anonymous.

What will happen to the results of the study?

The results of the study will be published in the scientific and clinical journals, conferences and the principle investigator's research thesis. They will also be fed back to health care professionals.

What do you do now?

If you wish to take part or if you have any questions or would like more information please do not hesitate to contact. Contact details are given below.

Miss Hannah Jarvis
Room PO30
Brian Blatchford Building
Fredrick Road Campus
University of Salford
M6 6PU
07866 033704
H.L.Jarvis@pgr.salford.ac.uk

A.2.3 Consent form for assessors

SALFORD RESEARCH
CONSENT FORM

Title of Project:

An investigation into the inter-reliability of the biomechanical examination procedures used by Podiatrists in clinical practice.

Name of Researcher: Hannah Jarvis

Please initial box

1. I confirm that I have read and understand the information sheet dated..................... (version..................) 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.

5. I agree to take part in the above study.

Name of subject Date Signature

Name of Person taking consent Date Signature

Researcher Date Signature

A.2.4 Information sheet for participants

<u>Participant Information Sheet</u>

"Inter-reliability study day assessing the biomechanical examination protocol used by Podiatrists in clinical practice."

You are being invited to take part in a research study. Before you decide whether to participate it is important for you to understand why the research is being done and what it will involve.

Please take time to read the following information carefully. Please ask if there is anything that is not clear or if you would like more information.

Background to the study

Some health professionals diagnose foot health problems and design foot orthoses (insoles) based on ideas that were published in the late 1970's. These ideas have never been fully tested and we believe that improvements in these ideas are required. This would improve clinical practice in relation to foot health and improve the design and use of foot orthoses. The aim of this study is to assess the reliability between different assessors when performing the biomechanical examination protocol as used by Podiatrists in clinical practice.

Do you have to take part?

No. It is up to you to decide whether or not to take part. You are under no obligation.

Why you have been chosen?

We wish to recruit a wide range of people (different ages, gender, height, weight etc.) in the general population of people who are not currently experiencing any foot or lower limb problems.

What will happen to me if I take part?

Various biomechanical examination procedures of the lower limb, leg and foot will be performed on you, these are used routinely in clinical practice and will be performed by Podiatrists who specialise in Biomechanics.

What are the possible disadvantages and risks of taking part?

This study is very low risk. This assessment is routinely used in clinical practice.

What are the possible benefits of taking part?

This study will help decide if the biomechanical examination procedures used by Podiatrists in clinical practice are reliable and therefore implicate if they should be used in clinical practice.

What if there is a problem?

If you have concern about any aspect of the study the researcher (Hannah Jarvis) will do her best to answer any problems. Please contact her on H.L.Jarvis@pgr.salford.ac.uk, 07866 033704

What will happen if I do not want to participate in this study?

You can withdraw from the study at any time without giving a reason. Any data which has been collected data will be deleted.

Will my taking part in the study be kept confidential?

Yes. Any information obtained in connection with this study will be treated as privileged and confidential. All information will be kept anonymous.

What will happen to the results of the study?

The results of the study will be published in the scientific and clinical journals, conferences and the principle investigator’s research thesis. They will also be fed back to health care professionals.

What do you do now?

If you wish to take part or if you have any questions or would like more information please do not hesitate to contact. Contact details are given below.

Miss Hannah Jarvis

Room PO30, Brian Blatchford Building

Fredrick Road Campus

University of Salford

M6 6PU

07866 033704

H.L.Jarvis@pgr.salford.ac.uk

A.2.5 Consent form for participants

SALFORD RESEARCH
CONSENT FORM

Title of Project:

An investigation into the inter-reliability of the biomechanical examination procedures used by Podiatrists in clinical practice.

Name of Researcher: Hannah Jarvis

Please initial box

1. I confirm that I have read and understand the information sheet dated..................... (version..................) 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 agree to take part in the above study. ☐

Name of subject	Date	Signature
Name of Person taking consent	Date	Signature
Researcher	Date	Signature

A.3 An investigation into asymptomatic human foot, leg and lower limb function

A.3.1 University of Salford Research Ethics Panel (REP) reference: RGEC08/090

A.3.2 Participant information sheet

Participant Information Sheet

"An investigation into asymptomatic (pain free) foot, leg and lower limb function."

You are being invited to take part in a research study. Before you decide whether to participate it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Please ask if there is anything that is not clear or if you would like more information.

Background to the study

Some health professionals diagnose foot health problems and design foot orthoses (insoles) based on ideas that were published in the late 1970's. These ideas have never been fully tested and we believe that improvements in these ideas are required. This would improve clinical practice in relation to foot health and improve the design and use of foot orthoses. There improvements are possible now because we have measurement techniques available that were not available in the 1970's. We hope to measure various aspects of foot and leg function during walking, by which we mean the way the foot and leg move, how muscles act, and how pressure is applied to the bottom of the foot.

Do you have to take part?

No. It is up to you to decide whether or not to take part. You are under no obligation.

Why you have been chosen?

We wish to recruit a wide range of people (different ages, gender, height, weight etc.) in the general population of people who are not currently experiencing any foot or lower limb problems.

What will happen to me if I take part?

To participate you must not have any symptoms in your feet or legs at present, or history of musculoskeletal problems. We will help test this through a series of simple and common tests of your feet. This includes testing sensation with a tuning fork and testing whether you can perceive very light touch on the bottom of your feet. We will also feel for your foot pulses. We will ask you to complete a short questionnaire that is used across the world to assess foot health.

We will then ask you to walk barefoot in our laboratory whilst we measure the movements of and pressure beneath your feet. You will be required to wear shorts for the walking experiments.

- *Measurement of the foot motion*

Small plastic plates with reflective ‘balls’ mounted on them will be attached to your feet (please state if you have an allergy to selotape or adhesive strapping as you will not be able to take part). These will go on specific locations on your feet, for example around the heel. Special cameras in our laboratory are able to track movements of these shiny balls as you move.

- *Measurement of the pressure under your feet*

As you walk you will be asked to place your feet over two plates that measure the forces under your feet. The plates are perfectly flat and are flush with the surrounding floor.

- *Measurement of muscle activity:*

During this study the activity of the muscles at the back (calf) and front of your legs. This involves attaching small electrodes to your skin surface, these are the same as those used for monitoring heart rates and only measure electrical activity. We will need to gentley rub the surface of the skin where the electrodes are placed to make sure they can stick properly. This can causes a very mild irritation but is momentary. Please state if you experience any discomfort during this and we can take appropriate action.

In addition you will be asked to stand barefoot whilst a Podiatrist visually assess the position of various parts of your feet. They may also gently move parts of your feet to test the movements.

All of the above will be explained during the experiment and please ask questions if you are unsure about anything.

You will be required to walk for approximately 15metres about 40 times, if you feel tired, unwell or do not wish to complete the duration of the investigation your participation will cease and you can withdraw from the investigation without explanation.

What are the possible disadvantages and risks of taking part?

This study is very low risk. The study will be performed with advanced technical gait analysis equipment that is widely used in ur group to study walking and other movements.

What are the possible benefits of taking part?

This study will provide insight into how the human foot works This will improve both the quality of understanding of foot health but also improve the choice of treatments such as insoles. The project will also be used to improve the scientific quality of the education materials the University provides.

What if there is a problem?

If you have concern about any aspect of the study the researcher (Hannah Jarvis) will do her best to answer any problems. Please contact her on H.L.Jarvis@pgr.salford.ac.uk, 07866 033704

What will happen if I do not want to participate in this study?

You can withdraw from the study at any time without giving a reason. Any data which has been collected data will be deleted.

Will my taking part in the study be kept confidential?

Yes. Any information obtained in connection with this study will be treated as privileged and confidential. All information will be kept anonymous.

What will happen to the results of the study?

The results of the study will be published in the scientific and clinical journals, conferences and the principle investigator's research thesis. They will also be fed back to health care professionals.

What do you do now?

If you wish to take part or if you have any questions or would like more information please do not hesitate to contact. Contact details are given below.

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A.3.3 Consent form for participants

SALFORD RESEARCH
CONSENT FORM

Title of Project:
An investigation into asymptomatic human foot, leg and lower limb function

Name of Researcher: Hannah Jarvis

Please initial box

1. I confirm that I have read and understand the information sheet dated...................... (version...................) 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 members of the University of Salford research staff/student who are working on the project will only look at images of my walking. I give permission for these individuals to have access to this data. ☐

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

________________________ __________________________________

Name of subject Date Signature

________________________ __________________________________

Name of Person taking consent Date Signature

________________________ __________________________________

Researcher Date Signature

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