Characterization of sagittal plane calcaneal rotation and its relationship to the medial longitudinal arch during the midstance phase of gait.

by

Stacy Elizabeth Stamm

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

Faculty of Physical Education and Recreation
University of Alberta

Abstract

Rearfoot motion during gait may influence athletic footwear choices and injury prevention, yet rearfoot motion during stance has not been fully characterized. Rearfoot pronation is typically used to categorize arch types into structural and functional groups, yet the amount of rearfoot plantar flexion during stance has not been determined. The objective of this study is to characterize this motion of the calcaneus during the stance phase of gait and its relationship to arch type. The functional and structural foot arch types of thirty participants were characterized using a modified longitudinal arch angle (LAA) test. Segmental rotation was used to determine independent rotations of the calcaneus. Calcaneal plantar flexion was found during the midstance phase. Possible relationships to functional or structural arch types were identified. This signifies the importance of calcaneal plantar flexion in characterizing foot arch type and of using segmental analysis in identifying key bone rotations.

Keywords: Flatfoot, Calcaneus, Gait, Foot type, Medial Longitudinal Arch

Preface

This thesis is an original work by Stacy Stamm. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "The relationship between heel bone movement and foot arch type during walking.", No. PRO00039038, June 11, 2013.

Contents

List of Tables

List of Figures

Chapter 1 : Introduction

Introduction

Background

Foot arch type is used to identify the structural and functional characteristics of a person's foot. It is theorized that foot arch type will influence mechanics during activities of daily living, sport, and exercise (M. Razeghi & Batt, 2002). Further, there is evidence that certain foot arch types are associated with injury (Burns, Keenan, & Redmond, 2005; Williams Iii, McClay, & Hamill, 2001). In practice, a number of methods are used to classify foot arch type, which may then be used to recommend footwear (Butler, R. J., Davis, I. S., & Hamill, J., 2006), orthotics (Bates, B. T., Osternig, L. R., Mason, B., & James, L. S., 1979; Razeghi, M., & Batt, M. E., 2000) or to prescribe exercise for either prevention of or rehabilitation from injury (Kaufman, Brodine, Shaffer, Johnson, & Cullison, 1999). Common methods of measuring foot arch types include arch foot prints, navicular drop, and longitudinal arch angle (LAA) (Williams, D. S., & McClay, I. S., 2000). However, a limitation of these foot arch type measurements is that the bony mechanics within the foot are not well understood (M. Razeghi & Batt, 2002). Thus identifying optimal interventions, such as athletic shoes or orthotics, for different foot arch types is not optimal.

The traditional theory of foot bone mechanics relevant to arch type is the mitered-hinge theory proposed by Inman (Stiehl & Inman, 1991). This theory states that calcaneal eversion will be coupled with shank internal rotation through the talocrural articulation (Pohl, M. B., Messenger, N., & Buckley, J. G., 2006). It is further believed that calcaneal eversion will destabilize the calcaneocuboidal and talonavicular joints resulting in collapse of the mid- and forefoot (Lundgren, P., Nester, C., Liu, A., Arndt, A., Jones, R., Stacoff, A., ... & Lundberg, A., 2008). These combined rear-, mid- and forefoot motions is called pronation (Lundberg, A., Svensson, O. K., Bylund, C., Goldie, I., & Selvik, G., 1989). Overpronation refers to excessive pronation while underpronation and supination refer to lack of intersegmental foot motion.

In practice, individuals are categorized using foot arch type measurements as having neutral, overpronating, or under pronating feet and then placed in shoes or prescribed orthotics which attempt to place or maintain the foot in a neutral position. Overpronating feet are commonly believed to be the most frequent foot arch type, particularly in athletes, like runners, where the incidence of injury is high. A "stability" shoe for an overpronating foot has a "medial posting" which is designed to prevent calcaneal eversion during activities such as gait and running (Genova, J. M., & Gross, M. T., 2000; Johanson, M. A., Donatelli, R., Wooden, M. J., Andrew, P. D., & Cummings, G. S, 1994). Yet matching an athlete's foot type to a shoe that should prevent injury has been shown to have no effect on injury rates (McKenzie, D. C., D. B. Clement, and J. E. Taunton., 1985; Richards, Magin, & Callister, 2009; Williams Iii et al., 2001). Since a relationship between injury rates, shoe type, and foot arch type has not been found, a better understanding of the movement of the foot may be necessary.

Recent research suggests that different foot arch types have small differences in calcaneal eversion during dynamic activities such as gait (Hunt, A. E., & Smith, R. M., 2004; Powell, Long, Milner, & Zhang, 2011; Wilken, 2006). Further, the amount of calcaneal eversion in a healthy population is less than previously believed (Goto, A., Moritomo, H., Itohara, T., Watanabe, T., & Sugamoto, K., 2009; A. Lundberg, 1989; Lundgren, P., Nester, C., Liu, A., Arndt, A., Jones, R., Stacoff, A., ... & Lundberg, A., 2008; Wong, Y., Kim, W., & Ying, N., 2005), making it unlikely that calcaneal eversion and the mitered-hinge theory are the primary determinant for different foot arch types and the injuries associated with the foot arch. The primary support for the medial longitudinal arch (MLA) of the foot is the plantar fascia, accounting for 80% of the force resisting arch collapse (Laquinto, J. M., & Wayne, J. S., 2010; Thordarson, Schmotzer, Chon, & Peters, 1995). Tension in the plantar fascia, and therefore support for the MLA, is controlled via dorsiflexion of the toes which is known as the Windlass mechanism (Caravaggi, Pataky, Goulermas, Savage, & Crompton, 2009). Hicks described that increasing tension in the plantar fascia through the Windlass mechanism would raise the MLA through dorsiflexion of the calcaneus (Hicks, 1954). Similarly, weight-bearing would cause the plantar fascia to stretch, decreasing MLA height through calcaneal plantar flexion.

Despite the well-recognized phenomena of the Windlass mechanism, there has been little research to study calcaneal sagittal plane motion during weight-bearing tasks where arch collapse would occur. Sagittal plane ankle joint rotation is a common measure in gait and running studies, for example analyzing the relative motion of the shank (tibia and fibula) and calcaneus (Reinschmidt, C., Van Den

Bogert, A. J., Lundberg, A., Nigg, B. M., Murphy, N., Stacoff, A., & Stano, A., 1997). However, as the shank and calcaneus may rotate independently of each other, the true motion of the calcaneus may be obscured by evaluating ankle joint rotation. Recently, Chizewski and Chiu reported that the calcaneus plantar flexed while the shank dorsiflexed in a partial squat task, supporting the independent rotations of each segment (Chizewski & Chiu, 2012). Taken together, these researchers suggest sagittal plane calcaneal rotations may play a mechanistic role in foot arch type.

Motivation

In order to better prescribe intervention for individuals with foot arch types impairing performance or increasing injury risk, the bony mechanics of different foot arch types should be better understood. The lack of research on sagittal plane calcaneal rotation during gait, in particular as a mechanism contributing to foot arch type, leaves a gap in the necessary knowledge for understanding foot arch type. Currently foot arch type is based on a theory of calcaneal frontal plane rotations without sagittal plane involvement while interventions are designed to address excessive or lack of frontal plane rotation. If sagittal plane rotations contribute to foot arch type, new methods could be determined to address performance and injury issues associated with foot arch type. These methods could involve increasing or decreasing sagittal plane calcaneal motion based on the difference foot types, such as a wedge in front of the calcaneus.

Scope

Rotations of segments of the foot, specifically sagittal plane rotation of the calcaneus, were measured during the stance phase – and midstance sub-phase – of gait using a seven-camera motion analysis system with thirty retro-reflective skin markers. The MLA was measured by goniometer using a quasi-static longitudinal arch angle (LAA) measurement. Functional and structural arch type was determined based on the LAA change from a seated position to a single leg standing position and the LAA at single leg standing, respectively. Correlation analysis was used to compare structural (LAA) and functional (calcaneal rotation) measurements during this phase of gait. Since this is a relational study, no independent variables were manipulated.

Participants were sampled from a convenience sample of the University of Alberta population. Participants who had foot arch types which fell between normal to flexible flatfoot were included. Individuals who had rigid feet were not included in this study as it was expected that they would have little or no inter-segmental foot motion (Arangio, G. A., Chen, C., & Salathé, E. P., 1998).

Limitations

This study was limited by the methods and the participants performing the tasks. Optoelectronic motion analysis was used to evaluate foot mechanics. To accomplish this, markers are placed on the skin to represent important bony landmarks. Skin markers may be a good representation of underlying bone movement depending on the magnitude of motion between the skin and bone. Reinschmidt et al. found good agreement, particularly in the sagittal plane, for tibiocalcaneal joint angles during gait comparing markers on the shoe versus bone pin mounted markers (Reinschmidt, C., Van Den Bogert, A. J., Lundberg, A., Nigg, B. M., Murphy, N., Stacoff, A., & Stano, A., 1997). Okita et all has also found good agreement between bone pin mounted markers and the skin marker set used in this study with regard to calcaneal rotations (Okita, N., Meyers, S. A., Challis, J. H., & Sharkey, N. A., 2013).This study used a cluster-based method for marker placement which allows markers to be placed on segments where minimal skin motion occurs. Recent research shows good agreement for calcaneal rotations measured using skin-mounted calcaneal markers and bone pin-mounted markers in a cadaver model (Okita, N., Meyers, S. A., Challis, J. H., & Sharkey, N. A., 2013).

Characterization of foot arch type is a difficult task that has not been standardized. The LAA has been shown to have high inter- and intra-tester reliability and represents dynamic movement well (McPoil & Cornwall, 2005), yet it is not a perfect method for categorizing foot arch type. No characterization method has been chosen as a gold standard because functional differences between foot arch types are not fully understood. This study aimed to increase this understanding of the functional differences between foot arch types.

The participants for this study were a convenience sample of mainly university students and staff so it is not representative of the general population. Anytime a participant is performing a task in a lab, the task may be altered from what is normally performed. Participants may walk faster or slower than normal to try and perform their gait as best as possible. This change in rate could affect the resulting calcaneal rotations due to differences in calcaneal tendon tension. To mediate this, participants were allowed adequate practice time to minimize any error due to this as well as their gait speed was monitored to be within the normal range.

Definitions

Pronation and supination are used to describe multi-planar rotation within the foot. These terms will only be used when all three related rotations are occurring. Pronation includes eversion, dorsiflexion, and abduction of a segment, while supination includes inversion, plantar flexion, and adduction.

MLA movement and structure terms will also be used throughout this study. Arch structure is the overarching term defining the shape of the MLA and measured using the LAA. Increase of the arch structure is a rise of the MLA away from the floor and an increase in LAA. A decrease or flattening of the arch structure is a lowering of the MLA towards the floor and comprises a decrease in LAA.

In biomechanical analysis, positive and negative rotations are defined as rotation of a segment coordinate system relative to a reference coordinate system. The right-hand rule was used for analyzing all rotations. However, sagittal plane rotations occurring on the left side were negated so the resulting anatomical rotations were the same for both sides. For this study, dorsiflexion and plantar flexion rotations occur around the X-axis, with dorsiflexion being positive rotation. Eversion and inversion are defined as rotation around the Y-axis, with eversion rotation as positive rotation. Finally, abduction and adduction are rotation about the Z-axis with abduction being positive rotation about the Z-axis.

Traditionally lower limb motion is studied by analyzing joint rotations and translations where a joint is the articulation between two segments. Yet this method does not evaluate the contribution of each segment to the resulting joint rotations. For this study, the rotations of segments were analyzed relative to the laboratory coordinate system rather than to each other. This is important because during swing and early stance phase of gait the shank and foot are mobile, yet once footflat occurs the foot is immobile and shank rotation accounts for all joint rotations occurring. Segment analysis allows the contribution of the individual foot segments to be determined during the early stance phase of gait.

Literature Review

Foot Structural Anatomy

The foot is made up of 26 major bones. These bones are the talus, calcaneus, navicular, cuboid, cuneiforms (3), metatarsals (5) and phalanges (14). The bones can be grouped into the rearfoot, midfoot, forefoot and phalanges. The rearfoot contains the talus and calcaneus. The midfoot includes the navicular, cuboid and three cuneiforms and the metatarsals make up the forefoot. These groups of bones form three arches in the foot, the medial and lateral longitudinal arches and the transverse arch. All three arches contribute to the static and dynamic support for the foot during activity. For the purpose of this study, the talus, calcaneus and navicular are the key bones analyzed while only the MLA was looked at (Figure 1-1).

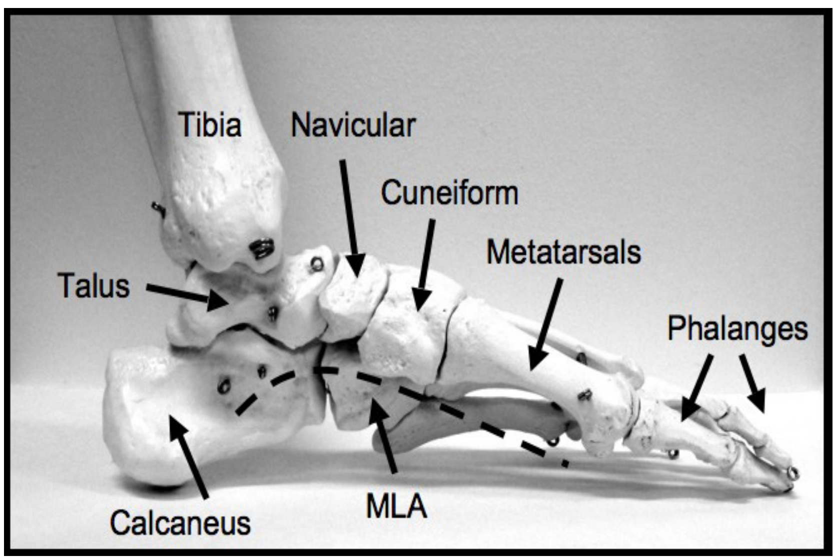


Figure 1-1: Diagram showing bones and the medial longitudinal arch of the foot.

The foot articulates with the rest of the body through the talus at the talocrural joint. The talocrural joint has the talus articulating with the fibula and tibia (or shank segment) through a mortise shaped joint. 90-95% of forces pass through the talo-tibial portion of the joint while the other 5-10% will pass through the talo-fibular portion (D. A. Neumann, 2010). By forming a mortise shape, the joint is limited to primarily dorsiflexion and plantar flexion about the transverse axis, which passes through the medial and lateral malleoli (Figure 1-2) (Hamel, Sharkey, Buczek, & Michelson, 2004; D. A. Neumann, 2010). The transverse axis of the talocrural joint is not perfectly aligned with the transverse axis of the body. On average, the medial malleoli is offset 84 degrees from the sagittal plane and the lateral malleoli averaging 89 degrees laterally from the sagittal plane (D. A. Neumann, 2010). The orientation of the transverse axis of the talocrural joint causes dorsiflexion and plantar flexion to involve multi-planar rotations (Scott & Winter, 1991). During dorsiflexion, the lateral malleolus translates posteriorly on the talus while the medial malleolus stays fixed, allowing for increased motion (Stiehl & Inman, 1991). Since the anterior portion of the talus is approximately 2.5 mm wider than the posterior portion, the joint stays stable while dorsiflexing, preventing the tibia and fibula from gliding anteriorly off of the talus while also limiting the maximum dorsiflexion allowed (Stiehl & Inman, 1991). While moving through dorsiflexion the foot will externally rotate and pronate if the tibia is fixed, or the tibia will internally rotate if the foot is fixed (Kepple, Stanhope, Lohmann, & Roman, 1990; Stiehl & Inman, 1991).

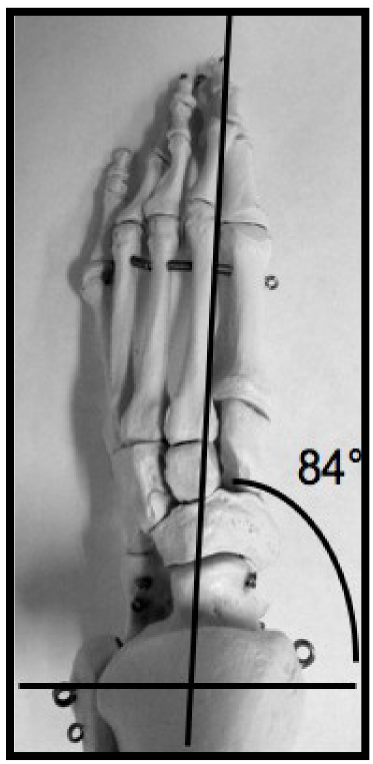


Figure 1-2: Diagram showing the axis of rotation for the talocrural joint.

During weight bearing, the talocrural joint supports the weight of the segments above it so it must be stable, which is provided by this mortise type joint. Between the distal portion of the tibia and the proximal end of the talus there is 3 mm of articular cartilage that will compress up to 40% at peak forces during weight bearing (D. A. Neumann, 2010). This helps to cushion the forces going through the foot as the body weight is applied (D. A. Neumann, 2010).

Inferiorly the talus articulates with the calcaneus via the subtalar joint. There are three articulations between the talus and the calcaneus; the posterior, middle and anterior articulations. The posterior articulation is the largest, containing over 70% of the articular surface between the bones (D. A. Neumann, 2010; Stiehl & Inman, 1991). All three articulations have their own joint capsule, which allow for improved support and stability (Stiehl & Inman, 1991). The subtalar joint mainly allows inversion and eversion of the calcaneus in relation to the talus with minor rotation in the other two planes (Piazza, 2005; Sheehan, 2010; Stiehl & Inman, 1991). The range of motion is greater in inversion compared to eversion due to the location of the lateral malleolus. Though the subtalar joint has been shown to allow rotations, many researchers believe the rotations to be minimal, rotating between 1-4 degrees (Hamel et al., 2004; D. A. Neumann, 2010; Piazza, 2005). Inversion and eversion at the subtalar joint occur about the sagittal axis. Similar to the transverse axis of the talocrural joint, the sagittal axis of the subtalar joint is not aligned with the sagittal plane of the body. Instead the sagittal axis of the subtalar joint is oriented 41 degrees (range 20-68 degrees) above horizontal and 23 degrees (range 4-47 degrees) medial of midline (Figure 1-3) (Czerniecki, 1988; D. A. Neumann, 2010; Piazza, 2005).

a.

b.

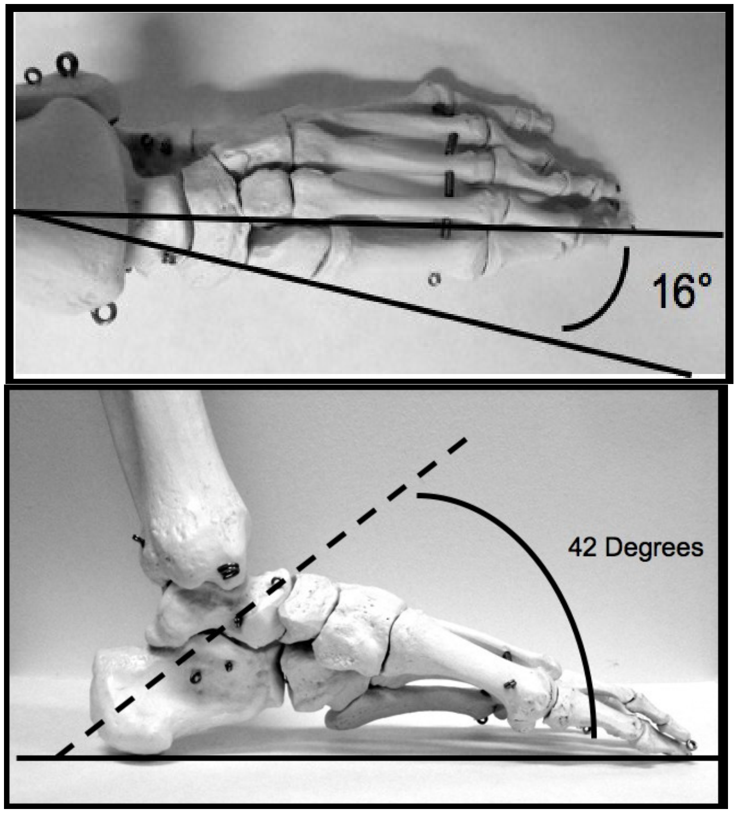


Figure 1-3: Diagram showing the axis of rotation of the subtalar joint in the transverse plane (a) and in the sagittal plane (b).

These movements of the talocrural and sub-talar joints are based on traditional descriptions (Stiehl & Inman, 1991). Traditional descriptions of movements are limited as only joint rotations were determined, motion was simulated in cadavers, and very basic methodologies used. To improve on these traditional descriptions, studies must look at segments rotations along with joint rotations, be performed in vivo rather than with cadaver simulations, and utilize up-to-date 3D motion analysis. Since methodology and technology have improved since the talocrural joint was originally studied, this movement should be reanalyzed to determine if the traditional movement is in fact the motion occurring. This study aims to help establish a physiologically relevant description of the rotations and translations occurring at the talocrural as well as subtalar joints during gait.

For the purpose of looking at the rotation of the calcaneus during gait, the talocrural and subtalar joints are the most important joints to understand. The function of the foot and rotations of these joints during gait will also be key in characterizing and understanding foot movement.

Foot Functional Anatomy

The foot can be modeled as either a rigid body with rotations occurring at the talocrural and subtalar joints or as a deformable body with many inter-segmental rotations. The foot is traditionally modeled as a single rigid body with no inter-segmental movement occurring (Winter, 1991). However many different studies have investigated complex models of the foot which account for deformation of the foot (Bruening, Cooney, & Buczek, 2012; Park & Stefanyshyn, 2011; Stebbins, Harrington, Thompson, Zavatsky, & Theologis, 2006). Collectively these rotations within the foot present as a change in the MLA of the foot with bone rotations occurring in the proximal and distal portions of the arch (Winter, 1991). Because of this, many studies have looked into modeling the foot as three separate rigid segments, the rearfoot, midfoot, and forefoot, yet how these segments are defined is controversial (Wrbaškić & Dowling, 2007). For this study the rearfoot will include the calcaneus and talus, the forefoot will include all five metatarsals, and the midfoot will incorporate the remaining tarsal bones.

Aside from each segment of the foot being identified, the locations and actions of the arches within the foot are important to identify. The longitudinal arch can be split into two different sections, the medial longitudinal arch (MLA) and the lateral longitudinal arch. The MLA begins at the calcaneus passing through the talus, navicular, and three cuneiforms and ends distally with the heads of the first three metatarsals (Tortora, Grabowski, & Aitf_veg, 2003). The keystone of the MLA is the navicular bone which articulates with the talus on the posterior portion and with the first cuneiform on the anterior portion (D. A. Neumann, 2010). The main support for the MLA comes from the passive support of the plantar fascia (D. A. Neumann, 2010). The lateral longitudinal arch does not allow as much motion as the MLA. It starts at the calcaneus and runs along the lateral side of the foot through the cuboid and to the heads of the 4th and 5th metatarsals (Tortora et al., 2003).

MLA structure changes mainly at the talonavicular joint, as the talus and navicular rotate within the local sagittal plane (Gray, Lewis, & Uahlthsc, 1918). The other segments within the arch then will rotate in their respective sagittal planes, though these rotations are smaller than those at the talonavicular joint. The interlocking tarsal joints, the plantar fascia, the plantar ligaments of the foot, and the spring ligament are the main supporting structures of the MLA (Chu, Myerson, Nyska, & Parks, 2001; Huang, Kitaoka, An, &

Chao, 1993). The calcaneonavicular ligament is the main ligament supporting the talonavicular joint and allowing the arch to reform after flattening (Gray et al., 1918).

As previously identified, the plantar fascia provides the main passive support for the MLA (Kappel-Bargas, Woolf, Cornwall, & McPoil, 1998). The plantar fascia is located on the plantar surface of the foot, connecting the posterior calcaneus proximally to the heads of the first four metatarsals distally. When the proximal phalanges, particularly along the first ray, are dorsiflexed the plantar fascia will tighten (Hicks, 1954). This tightening causes the calcaneus to pull closer to the metatarsal heads and an increase in the MLA structure (Hicks, 1954). Hicks first recognized this phenomenon in 1954 and described it as a Windlass mechanism (Figure 1-4) (Hicks, 1954). The amount and force of dorsiflexion occurring at the metatarsals affects the amount of increase of the MLA height. When the first toe is dorsiflexed so that the plantar fascia is shortened by 1 cm, this causes a 1 cm translation of the calcaneus, which then increases the height of the arch structure (Hicks, 1954). With 350 N of dorsiflexion force at the first metatarsal head, a 3.6 degree decrease in the arch angle has been observed, while increasing the force to 700 N at the first metatarsal only causes the arch angle to decrease another 2.3 degrees (Thordarson et al., 1995). Therefore a curvilinear relationship exists between toe dorsiflexion and the increase in height of the MLA structure. Initiation of MLA movement may occur at different degrees of dorsiflexion of the first toe (Kappel-Bargas et al., 1998). In some feet, the MLA will start to move at a lower degree of dorsiflexion of the first toe then in other feet, creating two distinct groups (Kappel-Bargas et al., 1998). This trend is discussed more in-depth later as classification of foot arch type is examined.

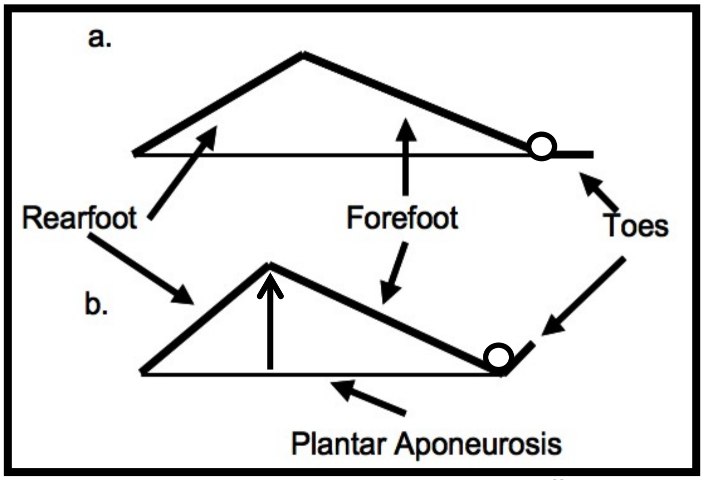


Figure 1-4: Diagram showing the windlass effect.

The plantar fascia and MLA are also directly related to the calcaneal tendon through the calcaneus. The plantar fascia attaches proximally to the posterior portion of the calcaneus, which is also the proximal bone in the MLA. The posterior portion of the calcaneus is also the distal attachment of the calcaneal tendon, which transmits the muscular forces from the soleus and gastrocnemius during gait. Through increased strain on the plantar fascia, dorsiflexion of the toes has been shown to increase stress at the calcaneal tendon (Cheng, Lin, Wang, & Chou, 2008). This occurs because the plantar fascia and calcaneal tendon have opposing actions on the calcaneus. Increasing the tension on the plantar fascia pulls the calcaneus into dorsiflexion, which pulls on the calcaneal tendon. Calcaneal tendon tension will plantar flex the calcaneus which has been show to increase strain on the plantar fascia. While 66-85% of the strain on the plantar fascia comes from dorsiflexion of the toes, tension in the calcaneal tendon accounts for 15-34% of plantar fascia strain (Cheng et al., 2008) (Figure 1-5).

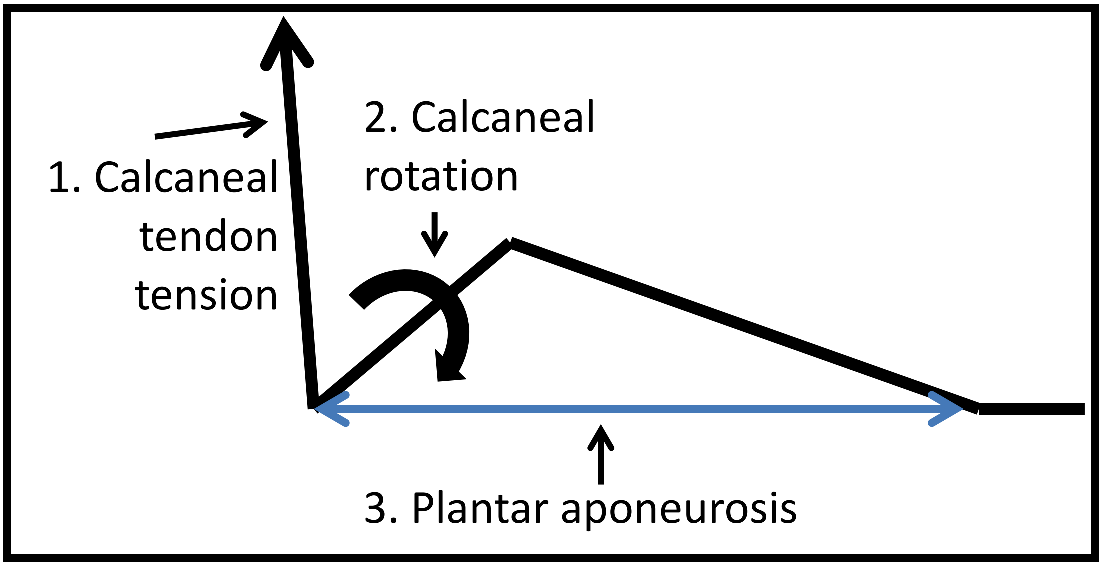


Figure 1-5: Diagram showing effect of calcaneal tendon tension on the plantar fascia.

Active plantar flexion of the ankle via the calcaneal tendon has been show to increase MLA height, yet the MLA will flatten when the ankle is plantarflexed passively (Iwanuma et al., 2011). This would occur because active plantar flexion of the ankle will plantar flex the calcaneus via the calcaneal tendon, while passive plantar flexion of the ankle may not rotate the calcaneus with respect to the foot. Tightening of the calcaneal tendon will plantar flex the calcaneus, causing the plantar fascia to pull the toes towards the calcaneus and the arch structure to increase. Yet passive plantar flexion of the foot on the tibia will not cause plantar flexion of the calcaneus so the arch will flatten since the calcaneus does not rotate and the plantar fascia is too loose to support the arch. This shows the importance of tension in the calcaneal tendon on the plantar fascia and MLA, and that active and passive rotations of the calcaneus directly affect the MLA.

Together, sagittal plane calcaneal rotation is influenced by proximal (calcaneal tendon) and distal (plantar fascia) structures. Since these soft tissues attach to other bones which do not directly articulate with the calcaneus it is important to look at the segmental rotations of the calcaneus and not just the traditional joint rotations. For example, identifying rotations at the subtalar joint may not show all rotations of the calcaneus. The calcaneal tendon and plantar fascia may cause segmental motion of the calcaneus in relation to a bony segment with which it does not directly articulate, such as the shank or thigh.

Foot Muscular Anatomy

Because the calcaneal tendon attaches to the calcaneus and therefore affects the strain on the plantar fascia and the MLA, it is important to identify the musculature affecting the tension on the calcaneal tendon. The two muscles which are important in gait that are part of the calcaneal tendon are the soleus and the gastrocnemius. Both insert to the calcaneus via the calcaneal tendon, yet they have different actions and functions as a result of their proximal attachment. The main difference between the two muscles is that the soleus originates on the tibia while the gastrocnemius crosses the knee joint and originates on the femur. The soleus contributes more to the physiological cross-section of the calcaneal tendon than the gastrocnemius, contributing 62% of the cross section compared to 38% for the gastrocnemius (Lersch et al., 2012). Because both muscles attach to the calcaneus by the calcaneal tendon, when shank and thigh are fixed, both the soleus and gastrocnemius perform plantar flexion of the calcaneus (Gray et al., 1918). If the calcaneus is fixed, the soleus will steady the shank upon the foot and prevent the body from falling over by plantar flexing the shank on the calcaneus (Gray et al., 1918). Yet with the calcaneus fixed, the gastrocnemius will instead flex the femur on the tibia, assisting the popliteus muscle in unlocking the knee joint (Gray et al., 1918). During gait the soleus decelerates the shank as it rotates forward over the foot between stance and pre-swing phase while the gastrocnemius helps to accelerate the thigh into flexion during midstance (Neptune, Kautz, & Zajac, 2001).

When comparing the gastrocnemius and soleus' actions during gait, they perform different actions because of their different origins. When the calcaneus is mobile, they will perform the same plantar flexion action of the calcaneus, yet their actions differ once the calcaneus is immobile, such as during the stance phase of gait (Gray et al., 1918). During early stance phase of gait the soleus works to prevent forward translation of the tibia over the talus while the gastrocnemius decelerates the shank and thigh (Neptune et al., 2001; Perry & Burnfield, 2010). During midstance, the gastrocnemius works to flex the knee and prevent rotation of the shank forward over the talus while the soleus assists with forward rotation of the shank with a near isometric contraction (Neptune et al., 2001). During this isometric contraction, the soleus causes proximal displacement of the calcaneal tuberosity (Iwanuma et al., 2011). Though the gastrocnemius and soleus cause different actions on the shank during gait, for this study, their most important action is causing plantar flexion of the calcaneus when the calcaneus is not fixed. This plantar flexion in turn tightens the plantar fascia and affects the MLA.

Foot Arch Types

Once the joints, ligaments, and muscles of the foot and ankle and their respective rotations and translations have been understood, variations in foot arch type can be classified. Feet can be classified by either their structural or functional differences outside of normal. The structural differences in foot arch type are affected by the shape of the bones and are not changeable, while functional differences are caused by differences in the muscles, ligaments or fascias within the foot and can be altered. Functional differences can only be identified when comparing a weight bearing foot to the foot in non-weight bearing.

Feet which are structurally different from normal can be classified as either pes cavus or pes planus. Both have little to no change in the MLA structure when moving from non-weight bearing to weight bearing (E. J. Harris et al., 2004). However pes cavus feet have a higher arch structure than a normal foot, while pes planus feet have a flatter arch than the normal foot (Figure 1-6). A pes planus foot is usually caused by mechanical uncoupling of tarsal bones or changes in bone shape (Huang et al., 1993). These structural differences can account for roughly 35% of differences in peak plantar pressure during walking (Cavanagh et al., 1997). This suggests the other 65% of differences in feet can be accounted for by functional differences.

a.

b.

c.

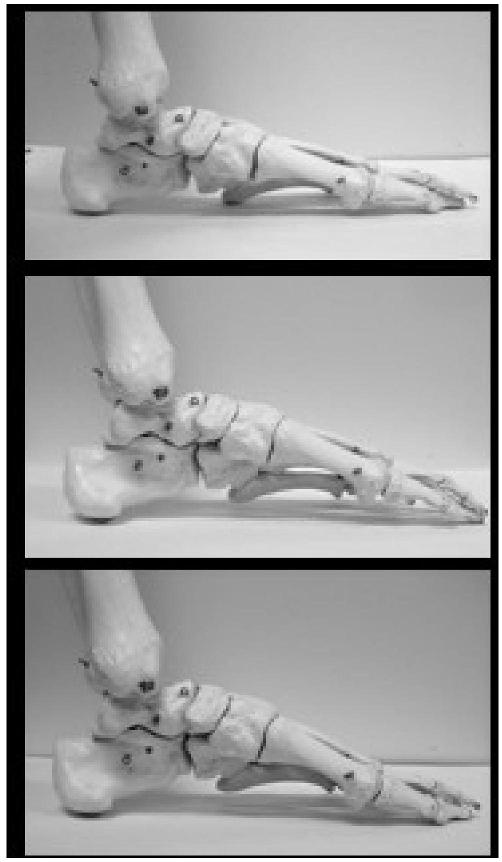


Figure 1-6: Drawings showing pes planus (a), normal (b), and pes cavus (c) feet from the medial side.

The main functional foot arch type that differs from the normal foot is the flexible flatfoot. A flexible flatfoot is structurally similar to a normal foot during non-weight bearing, yet during weight bearing the MLA will flatten so the foot will look like a pes planus foot (R. I. Harris & Beath, 1948; E. J. Harris et al., 2004; E. J. Harris, 2010). Because the foot acts differently based on the loading, it has been shown that there is a low correlation between static foot arch type classifications and dynamic foot movement. Flexible flatfoot can be identified by flexing the first toe during weight bearing. This flexion of the toe will cause the windless mechanism to stabilize the MLA and arch structure to return to the shape of arch (E. J. Harris et al., 2004). A loose plantar fascia may be one cause of flexible flatfoot, so flexing the first toe will cause the plantar fascia to tighten and the windlass effect to occur. In some cases these functional changes can be caused by a shortened calcaneal tendon and identified by decreased ankle dorsiflexion if the subtalar joint is held immobile (R. I. Harris & Beath, 1948). Increased cyclic loading of a flexible flatfoot can increase the amount of arch flattening which overstretches the plantar fascia (Chu et al., 2001). The main features of flexible flatfoot that have been studied are the movement of the MLA and the frontal plane rotation of the calcaneus. Increased inferior translation of the navicular in relation to the talus has been identified in flexible flatfoot (Gould, 1983; Kaufman et al., 1999). Excessive eversion of the calcaneus is shown to correlate with flexible flatfoot, as the foot is able to rotate more during walking (Nakamura & Kakurai, 2003). Though calcaneal tendon length has been shown to correlate with the occurrence of flexible flatfoot (R. I. Harris & Beath, 1948), the sagittal plane rotation of the calcaneus has not been looked at in relation to foot arch type. Since both the calcaneal tendon and plantar fascia tightness have been shown to differ in flexible flatfoot, sagittal plane rotation of the calcaneus is expected to be different as both these structures are attached to it.

Different foot arch types act differently during weight bearing tasks such as gait. The most dramatic changes occur when comparing a loaded and unloaded flexible flatfoot to a structural pes cavus or pes planus foot. The MLA structure in a flexible flatfoot will change when moving into weight bearing, while a pes cavus or pes planus foot will not (E. J. Harris et al., 2004). Because of these differences, injury rates based on foot arch type have been distinguished. Pes cavus feet have been shown to have more ankle, bone related, and lateral injuries due to their immobility and high peak plantar pressure, while pes planus and flexible flatfoot feet tend to have more knee, soft tissue, and medial injuries (Cavanagh et al., 1997; Williams Iii et al., 2001). Pes cavus feet have also been show to have increased rates of overuse injuries, though some studies have found pes planus feet to have high rates as well (Burns et al., 2005; Kaufman et al., 1999). Different location of stress fractures have also been shown to be different between foot arch types, with femoral and tibial stress fractures occurring more often with high-arched feet, while metatarsal stress fractures occurring more in low arched feet (Nigg, Nurse, & Stefanyshyn, 1999).

Measurement of Foot Arch Type

Though foot arch types have been well identified based on their structural and functional differences, classifying a specific foot into these types has not been standardized. There are three common methods to measure and classify foot arch type. A common element of each method is that the measurements must be normalized to foot length (M. Razeghi & Batt, 2002). All measurements are also taken on both the left and right foot, as foot arch type has been shown to differ between feet of the same individual (Nilsson, Friis, Michaelsen, Jakobsen, & Nielsen, 2012). Further, it is suggested that foot arch type measurements should be taken during dynamic situations to properly classify the foot during movement (M. Razeghi & Batt, 2002). The rationale for dynamic measurements is that static measurements have been shown to poorly correlate with function during dynamic movements (Kaufman et al., 1999). Static measurements are taken while the subject is standing still during weight bearing with weight evenly on each foot, while a dynamic measurement is taken while the subject is performing a functional task, such as walking. In addition to static or dynamic measures, a quasi-static measurement can be performed. A quasi-static measurement is a modification of a static measure, however the measurement is taken during non weight bearing and full weight bearing on the single foot, then the two measurements are compared. For example, this allows flexible flatfoot to be identified without performing a complete dynamic movement.

The arch index method is the most common method to classify foot arch type. For this method, the subject stands or walks on a paper or pad to create a footprint of their foot. The midfoot area is then identified as the middle third of the foot (Figure 1-7). The area of the midfoot which is imprinted on the paper is compared to the total area of the foot in the footprint. The percentage of the area that the midfoot covers is the arch index. Feet with arch index values between 0.21 and 0.26 are considered normal feet, while feet values below 0.21 have high arches and above 0.26 have low arches (Cavanagh & Rodgers, 1987). This method can be performed in standing or during walking or running, though it can only identify the maximum amount of the foot on the ground during the entire activity and cannot be used to identify arch structure instantaneously (Cavanagh & Rodgers, 1987; C. K. Wong, Weil, & de Boer, 2012). Because of this, the arch index method has been shown to poorly explain dynamic differences between subjects (M. Razeghi & Batt, 2002)

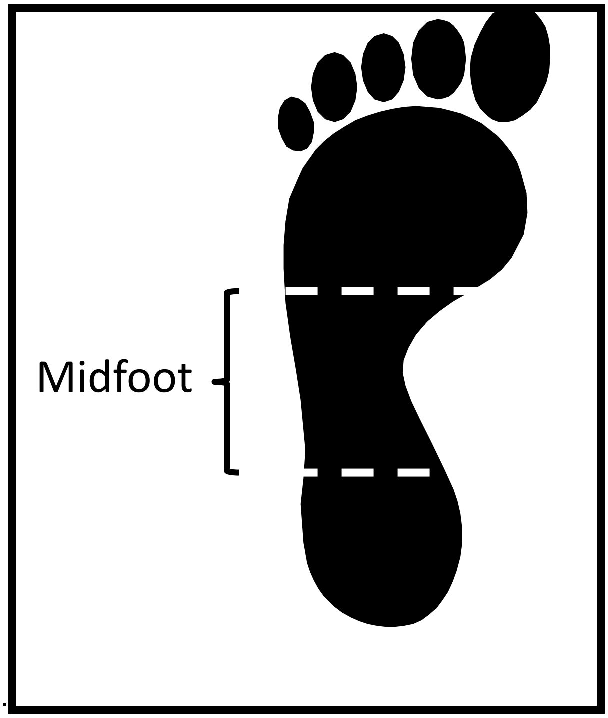


Figure 1-7: Diagram showing location of midfoot for calculation of arch index where the midfoot is the middle third of the foot based on total length.

Another frequent method for foot arch type characterization is the navicular drop method. This test is most often used in clinical situations due to its simplicity. For this method, the navicular bone is assumed to be the highest point of the MLA (M. Razeghi & Batt, 2002). The navicular tuberosity is palpated and marked and the sagittal plane translation of the navicular is measured between non-weight bearing and weight bearing. The initial position and this change are then used to classify the foot based on previously recorded navicular drops (M. Razeghi & Batt, 2002). This method provides moderate to poor reliability since it relies on such a small change being measured (M. Razeghi & Batt, 2002). The method also relies on the clinician being able to identify subtalar joint neutral in the non-weight bearing position, which can be difficult (M. Razeghi & Batt, 2002).

The arch index describes the horizontal dimensions of the MLA, while the navicular drop examines only the vertical components. Longitudinal arch angle is another method for characterizing foot arch type which measures both the horizontal and vertical changes. The medial malleolus, navicular tuberosity, and head of the first metatarsal are palpated and marked on the subject. The angle between the malleolus and navicular tuberosity and the navicular tuberosity and head of the first metatarsal is then measured, with the navicular tuberosity as the center point (Figure 1-8) (Cavanagh & Rodgers, 1987; McPoil & Cornwall, 2005). This angle can then be used to classify the foot. This method can be used as the subject is standing still and the angle measured with a goniometer or reflective markers can be placed on the landmarks and two- or three-dimensional motion analysis can be performed to measure the angle during different actions. Though other methods have shown to have low static to dynamic correlations, the static measurement for this method has shown to account for 90% of variations during walking (McPoil & Cornwall, 2005). This method has also been shown to have a 90% intra-examiner reliability (ICC) (Cavanagh & Rodgers, 1987). The average mean angle for different studies has been shown to be 141.61 degrees with a normal foot being classified within $\pm$1 standard deviation (7.67 degrees) of the mean (Cavanagh & Rodgers, 1987). Anything outside this normal range is then classified as a flexible flatfoot, pes cavus, or pes planus foot based on the resulting measurements. This method provides more information than the navicular drop and arch index methods because it looks at both the height and length of the MLA, however it is not traditionally used as a dynamic measurement (M. Razeghi & Batt, 2002).

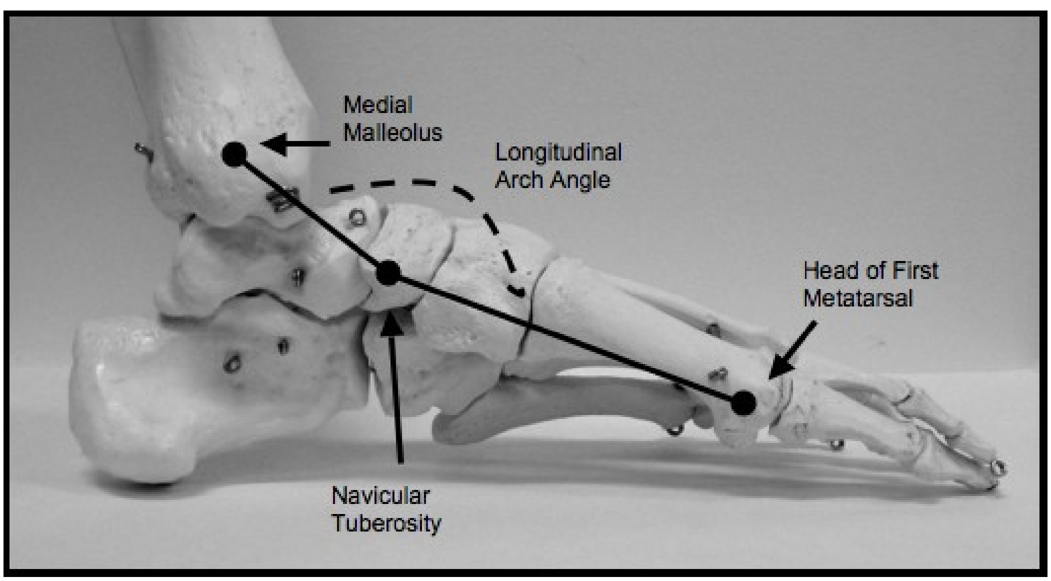


Figure 1-8: Image of the location of landmarks and longitudinal arch angle measurement.

A variation of the longitudinal arch angle method is the navicular position test (Spörndly-Nees, Dåsberg, Nielsen, Boesen, & Langberg, 2011). For this method the first metatarsal head and navicular tuberosity are marked the same, however a spot on the calcaneal tendon at the height of the medial malleolus is marked as the third landmark (Figure 1-9). The angle between these vectors is then measured. A straight line (180 degrees) is classified as normal, while any increase above 180 degrees is a pes cavus foot and any angle below 180 degrees is considered a flexible flatfoot or pes planus foot. The mean difference from 180 degrees was found to be 0.91 degrees above 180 degrees, with a range of -0.06 -1.88 degrees. This method has been shown to have 94-95% intra- and inter-reliability (Table 1-1) (Spörndly-Nees et al., 2011).

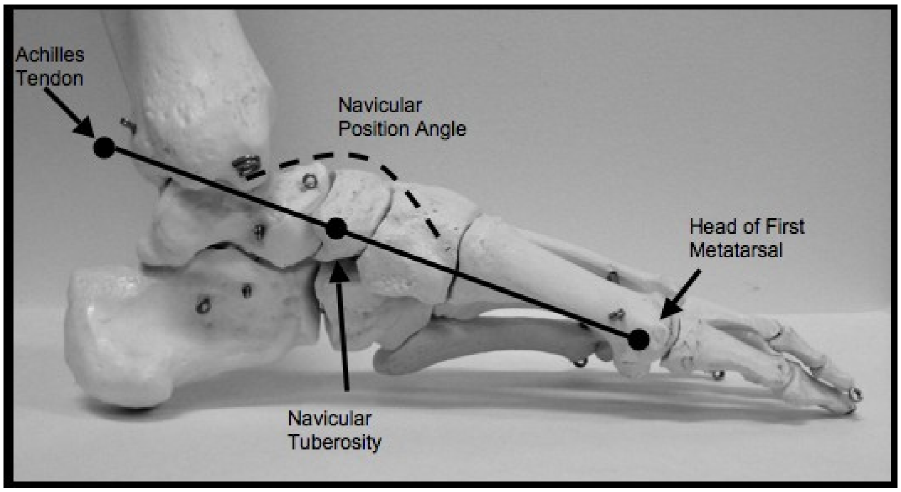


Figure 1-9: Image showing the location of the markers for the navicular position test and the angle to be measured.

Table 1-1: Comparison Arch Measurement Methods

Test	Variable	Mean	Outside Normal	Reliability
Arch Index (Cavanagh & Rodgers, 1987; Fascione, Crews, & Wrobel, 2012)	% Midfoot/Whole foot on ground	0.230 SD = 0.0463	High Arch ≤ 0.21 Flat Arch ≥0.26	74-99%
Navicular Drop (Picciano, Rowlands, & Worrell, 1993; Trimble, Bishop, Buckley, Fields, & Rozea, 2002)	Sagittal plane drop in navicular tuberosity position	7.3 mm SD = 4.2 mm	Flexible Flatfoot ≥10 mm High Arch ≤4 mm	57-79%
Longitudinal Arch Angle (Jonson & Gross, 1997; McPoil & Cornwall, 2005)	Angle between M. Malleolus, navicular tuberosity, 1st metatarsal head	141.76° SD = 7.67°	± 1 SD	90%
Navicular Position Test (Spörndly-Nees et al., 2011)	Angle between Calcaneal tendon, navicular tuberosity, 1st metatarsal head	180.91° (179.94-181.88°)	Did not identify	94-95%

Foot Biomechanics in Gait

During gait, rotation of the calcaneus has an important influence on the movement of the proximal and distal segments of the foot including the medial longitudinal arch. Different foot arch types exhibit different bone segment rotations during gait, and rotation of the calcaneus has been shown to correlate with these changes (Nakamura & Kakurai, 2003). Calcaneal rotation is specific to the phase of gait since the calcaneus becomes relatively immobile after footflat.

At heel strike the ankle averages 4 degrees of plantar flexion with a standard deviation of 3 degrees (Kadaba et al., 1989). The MLA is at its highest when no weight has been applied yet (Gray et al., 1918). Just before heel strike occurs the vertical and horizontal velocities of the heel slow down nearing zero before stopping completely as heel strike occurs (Winter, 1991). The gastrocnemius is activated just before heel strike to help slow down this horizontal velocity (Winter, 1991). Following heel strike, the tibia and fibula medially rotate 18 degrees on the talus (R. A. Neumann, 1975). Due to the action from the gastrocnemius and the ground reaction forces, the calcaneus then rotates out of its inverted position and within the first 8% of gait after heel strike pronates 10 degrees (Rodgers, 1988). As the calcaneus is everting and the talus, tibia, and fibular are medially rotating, the MLA begins to flatten from the vertical force caused by body weight being applied to the foot and from these rotations (Gray et al., 1918). In different feet type, this decrease in arch structure may vary depending on the structure of the foot and the length of the plantar fascia and calcaneal tendon. Structurally limited feet, pes cavus or pes planus, will not change arch structure as much as normal feet since their calcaneuses are immobile due to structural changes, while flexible flatfoot will see increased flattening since they do not have any structures preventing rotation (E. J. Harris, 2010).

After heel strike the foot rotates to footflat where the calcaneus is limited from additional rotation. During footflat up to 14 degrees of dorsiflexion will occur at the ankle joint, while the subtalar joint everts (D. A. Neumann, 2010). Most of this eversion comes from the talus and navicular bones as they rotate about the immobile calcaneus. As the subtalar joint is everting, the tibia will abduct with respect to the talus to counteract the rotation at the subtalar joint and keep the shank stable (Moseley, Smith, Hunt, & Gant, 1996). Near the end of footflat, the tibia will laterally rotate in relation to the foot, causing the talus to laterally rotate on the calcaneus as well and the foot to invert (Rodgers, 1988). This inversion locks the transverse tarsal joint and causes the MLA structure to increase preparing the foot for the forces at toe-off (Rodgers, 1988). From footflat to toe off, the MLA continues to flatten and lengthen until the plantar flexors are activated at toe-off (Rodgers, 1988). Both the soleus and gastrocnemius are active during footflat phase (Winter, 1991). This activation should cause the MLA to flatten further as the soleus and gastrocnemius act through calcaneal tendon which plantar flexes the calcaneus in relation to the floor. The gastrocnemius also works to control the forward rotation of the shank over the foot as well as allow for the knee to flex (Winter, 1991). The soleus will also control the forward rotation of the shank over the foot and at the end of footflat, provides the majority of the push off force necessary for toe-off (Winter, 1991).

Calcaneal Rotation

Frontal plane joint rotation of the calcaneus in relation to the tibia has been studied extensively in biomechanics research, particularly during gait. The rotation of the calcaneus is typically looked at in relation to the tibia rather than the talus, since motion at the subtalar joint is difficult to identify with noninvasive methods. Immediately prior to heel strike in gait, the calcaneus has been show to be slightly inverted relative to the tibia, ranging from 5-8 degrees of inversion at heel strike (Hamel et al., 2004; Leardini, Benedetti, Catani, Simoncini, & Giannini, 1999; Leardini et al., 2007; Moseley et al., 1996; Nakamura & Kakurai, 2003). The calcaneus then everts in relation to the tibia so that it is maximally everted at 57% of stance at 7.3 degrees of eversion (Moseley et al., 1996). Research has shown that calcaneal rotation in the frontal plane is approximately 11 degrees during a gait cycle (Moseley et al., 1996). One study using cadavers looked at the specific rotations of the subtalar joint, showing that at heel strike the calcaneus is everted relative to the talus at 1 degree of eversion, with the subtalar joint rotating to its neutral position at 25% of stance phase and no frontal plane subtalar rotation occurring for the rest of the stance phase (Hamel et al., 2004). Rearfoot eversion has been correlated with MLA structure, with later and more calcaneal eversion being correlated with increased flattening of the MLA (Nakamura & Kakurai, 2003). This increased movement of the MLA is indicative of a flexible flatfoot foot arch type. Since this research on calcaneal eversion and inversion during gait uses joint rotations in relation to the talus or tibia rather than segment rotations, it is difficult to know whether it is the calcaneus itself moving or one of the other segments in the joint. An analysis of frontal plane calcaneal segment rotation during gait is necessary to determine the actual motion of the calcaneus.

Sagittal plane rotation of the calcaneus has been studied less extensively and no studies have looked at differences in sagittal plane rotation between foot arch types. Further, most studies only characterize sagittal plane rotation for the tibia relative to the foot or calcaneus, but do not identify the rotation of the calcaneus as an independent segment (Leardini et al., 2007). Since both the tibia and calcaneus are rotating during gait, it is important to look at their rotations as independent segments and not just as one single joint rotation. When looking at the calcaneus specifically it is, again, normally compared to the tibia or the lab and not in relation to the talus. The calcaneus has been shown to be dorsiflexed with respect to the tibia just before heel strike, then rapidly plantar flexing to between 5-7 degrees of plantar flexion at heel strike (Hamel et al., 2004; Imai et al., 2009; Leardini et al., 1999; Moseley et al., 1996). The only study to look at calcaneus rotation, in vivo, with respect to the laboratory coordinate system found that the calcaneus rotated through 5-18 degrees of plantar flexion as the ankle dorsiflexed while the foot was flat, resembling the portion of gait where the foot is flat (Chizewski & Chiu, 2012). These results correspond with Okita et al. who reported the calcaneus to plantar flex in gait simulations using cadavers. The calcaneus then dorsiflexes with respect to the tibia as the tibia rotates over the foot during footflat. During this phase the calcaneus will go through 5-16 degrees of dorsiflexion with respect to the tibia (Hamel et al., 2004; Imai et al., 2009; Leardini et al., 1999; Moseley et al., 1996). Finally at toe-off the calcaneus begins to plantar flex again as the calcaneal tendon pulls on the posterior portion. This action by the calcaneal tendon will cause the plantar fascia to tighten and the windlass effect to occur, increasing the structure of the MLA as toe-off occurs.

Conclusion

The plantar fascia and calcaneal tendon have been shown to have an effect on MLA structure, yet their connection with arch type has not been directly studied. Since the calcaneus is a bony structure within the MLA, rotations of the calcaneus should interact with the other bones of the MLA and cause a change in the structure. Calcaneal plantar flexion may cause a destabilization of the MLA through this bony interaction and cause the MLA to flatten while calcaneal dorsiflexion could cause the MLA to rise. Though the plantar fascia and calcaneal tendon have been shown to account for changes in the MLA structure, the connection to calcaneal sagittal plane rotation has never been made. This relationship may not have been made because calcaneal rotations have been traditionally determined by referencing its rotation to the tibia rather than as segmental rotation on its own. Further, this theory linking plantar fascia tension, calcaneal plantar flexion, and arch height suggests that distinct categorical arch types do not exist. Instead, an individual's arch type will fall along a continuum from rigid (i.e. no calcaneal plantar flexion) to flexible (i.e. maximum calcaneal plantar flexion). Therefore, this suggests that a relationship may exist between sagittal plane calcaneal rotation and arch height. This study will investigate the relationship between segmental rotations of the calcaneus with structural and functional MLA measures.

Purpose Statement

This study will investigate lower extremity segment rotations, specifically calcaneal plantar flexion, during the stance phase and midstance sub-phase of gait. Specifically, the spatiotemporal pattern of calcaneal plantar flexion will be identified. Further, the relationship between calcaneal plantar flexion to structural and functional arch types will be assessed.

Hypothesis

It is hypothesized that the calcaneus will plantar flex during the stance phase of gait. In particular, the calcaneus will plantar flex during midstance when the rear- and forefoot are in contact with the ground. Consequently, increased calcaneal plantar flexion during midstance will reflect greater deformation of the MLA. Therefore, due to either increased flexibility of the plantar fascia or tightness in the calcaneal tendon, calcaneal plantar flexion during midstance will be greater in a more flexible foot compared to a more rigid foot.

Chapter 2 : Journal Article

Introduction

Biomechanics research involves the description of human movement. To be relevant these biomechanical descriptions of movement should be anatomically applicable. To this end methodology has been developed to relate kinematic analyses and anatomy, specifically the description of joint rotations. Biomechanically, a joint is described as the rotation of one rigid body relative to another rigid body, where each rigid body is an anatomical segment. This definition implies that one segment is moving while the second segment is fixed. However, during multi-joint tasks both segments may be moving. Therefore, where both segments forming a joint are moving, kinematic analysis of joint motion is does not provide a thorough description of the resulting rotations. Kinematic analysis of joint motion only allows description of relative motion between two segments, rather than the motions occurring for each segment.

Recent research of joint motion highlights this ambiguity. For example, the terms parallel squat and 90° squat are used interchangeably in the exercise literature. A parallel squat requires the thigh segment to be parallel to the ground, whereas the 90° squat requires the knee to be flexed to an angle of 90°. A parallel squat and 90° squat are only equivalent if the shank segment does not rotate. Since the shank rotates forward during a squat, to perform a squat with the thigh parallel to the ground, the knee flexion angle must reach 105-119° or greater (Bryanton, M. A., Kennedy, M. D., Carey, J. P., & Chiu, L. Z., 2012). Thus a parallel squat requires greater than 90° knee flexion, so the two terms are not synonymous. Further analyses of activities involving squatting indicate that the shank and thigh rotate independently (Moolyk, A. N., Carey, J. P., & Chiu, L. Z., 2013). Therefore description of knee angle alone may lead to erroneous conclusions regarding shank and thigh rotations.

Similarly, analysis of ankle joint angle during squatting tasks may not be reflective of the rotations occurring in the segments comprising the ankle. The ankle is typically studied in biomechanics as rotation of the shank relative to the calcaneus (or rearfoot). In a squat task, the ankle is described as dorsiflexing. However, this ankle dorsiflexion is a combination of shank *dorsiflexion* and calcaneal *plantar flexion* (Chizewski & Chiu, 2012). Calcaneal plantar flexion may appear to be paradoxical to ankle dorsiflexion however, it serves an important function in performing the squat. Anatomically, the morphology of the ankle joint is restricted to 15-20°, which limits how much the shank can dorsiflex. Calcaneal plantar flexion reorients the ankle joint, which allows for greater shank dorsiflexion (Chizewski & Chiu, 2012).

This shank dorsiflexion accounts for 67-69% of ankle dorsiflexion during a squat, while calcaneal plantar flexion contributes the other 28-31% of ankle dorsiflexion (Chizewski & Chiu, 2012). Since shank dorsiflexion is larger than calcaneal plantar flexion, ankle dorsiflexion unequally reflects the rotation of the shank and obscures the plantar flexion of the calcaneus.

These examples show the importance of measuring individual segment rotations rather than just joint rotations to describe human movement. Rotation of the shank affects how much the thigh rotates, even when the knee joint angle is the same (Moolyk, A. N., Carey, J. P., & Chiu, L. Z., 2013). If joint rotation only were measured at the knee, the actual thigh and shank segment rotations would not be identified. Similarly, ankle joint angle does not accurately reflect shank and calcaneal rotations. The larger shank rotation obscures calcaneal rotation, specifically that the calcaneus plantar flexes not dorsiflexes, during ankle dorsiflexion (Chizewski & Chiu, 2012).

Calcaneal Plantar Flexion

As there is a dearth of research describing rotations of the calcaneus segment, little is known regarding its anatomical relevance. The calcaneus is part of the rearfoot complex of the foot and acts as the rear portion of the medial longitudinal arch (MLA) (Tortora et al., 2003). Structurally, the rearfoot articulates proximally with the shank and distally with the midfoot. Therefore, calcaneal plantar flexion would not only influence rotation of the shank, but also rotation of the midfoot. Differences in sagittal plane calcaneal alignment have been reported on radiographs of different foot arch types (Harris, R. I., & Beath, T., 1948; Meehan, R. E., & Brage, M., 2003; Roth, S., Roth, A., Jotanovic, Z., & Madarevic, T., 2013). Flat feet have a lower calcaneal inclination, synonymous with a plantar flexed calcaneus, than normal feet. Radiographs of feet with lower calcaneal inclination will also have altered orientations of the midfoot bones and the metatarsals. This suggests that calcaneal plantar flexion may be anatomically relevant in relation to foot arch types.

Feet are often classified based on their arch types which is done based on visual appearance, measurement of foot shape, or measurement of various bony landmarks. Traditionally, arches are categorized as normal, pes planus (low arch), or pes cavus (high arch) (M. Razeghi & Batt, 2002). The clinical method of classifying arch type relies on visual appearance and normally occurs in a clinical setting involving a physician evaluating a patient complaining of foot pain or lower extremity dysfunction (Harris, R. I., & Beath, T., 1948). Quantitative methods assign numerical parameters to either foot shape or orientation of bony landmarks and then classify arch type statistically (M. Razeghi & Batt, 2002). Pes planus and pes cavus are considered abnormal, differing by one to two standard deviations away from the mean. Examples of quantitative methods commonly used include the navicular drop test, the arch index, and the longitudinal arch angle measurement.

Whether clinical or quantitative, classifying arch type is typically performed standing. However, it is known that the visual appearance of the foot changes between sitting and standing as well as between standing with the feet flat and standing on the toes (Harris, R. I., & Beath, T., 1948).This suggests that the relative alignment of bones in the foot may change as a function of internal (i.e. muscle) and external (i.e. gravitational) forces. Therefore, arch type, which reflects the relative alignment of foot bones, may vary both structurally and functionally.

Functionally, arch types are described as flexible and rigid. Functional characteristics of arch types can be measured using two methods - quasi-static and dynamic. The quasi-static method involves the same quantitative methods described above. However, measurements are taken in both non-weight bearing (NWB) and weight bearing (WB) positions. Flexible arches would have a large difference between NWB and WB measurements indicating a change in foot shape and bony orientation. Rigid arches would have little difference between NWB and WB measurements. The most common method for performing this quasi-static test is the navicular drop test, which measures the height of the navicular tuberosity relative to the ground when sitting and standing (Picciano et al., 1993). Dynamically, functional characteristics of the arch are measured using video analysis techniques. The dynamic method attempts to characterize changes in the arch during activity, rather than in two distinct positions (Fascione et al., 2012).

If structural and functional arch types are independent, several different combinations of arch type may be possible. Specifically, arches can vary structurally as pes planus, normal, and pes cavus, as well as range from rigid to flexible on a functional continuum (Table 2-1). Classifying feet using both functional and structural classifications is rarely performed.

Table 2-1: Theoretical Classification of Arch types based on Functional and Structural Characteristics

	Pes Planus		**Normal**		**Pes Cavus**	
	At NWB	**To WB**	**At NWB**	**To WB**	**At NWB**	**To WB**
Rigid	Low arch	No change arch height	Normal arch	No change arch height	High arch	No change arch height
Flexible	Low arch	Decrease arch height	Normal arch	Decrease arch height	High arch	Decrease arch height

Most research makes no distinction between functional and structural arch type. The same measurement is commonly used to describe structural arch type in one study, while describing functional arch type in another. For example, calcaneal inclination at weight bearing during X-ray has been used to describe a pes planus foot and a flexible foot, which are structural and functional classifications, respectively (Harris, R. I., & Beath, T., 1948; Meehan, R. E., & Brage, M., 2003; Roth, S., Roth, A., Jotanovic, Z., & Madarevic, T., 2013). Distinguishing between functional and structural types is difficult to do with some methods, and can sometimes get confused. A flexible normal structural arch measured in weight bearing may appear similar to a structural pes planus arch.

In addition to poorly discriminating between functional and structural arch types, many arch measurements may not realistically describe foot bone motion. For example, the arch index method for classifying foot arch type measures the area of the midfoot touching the ground relative to area of the rear- and forefoot touching the ground (Cavanagh & Rodgers, 1987). This method does not provide any information about the rotations and translations of the bones, just the location of the soft tissues (M. Razeghi & Batt, 2002). Another example is the navicular drop test, where the height of the navicular tuberosity is measured sitting and standing. This test assumes the navicular translates only along a vertical axis, however, the height of the navicular tuberosity may also change when the navicular rotates in the frontal plane (Trimble et al., 2002).

The inability to accurately characterize bony motion in the foot impairs the ability to understand foot arch types during human movement. Recently, Okita et al. reported that the calcaneus plantar flexes during mid-stance in gait. Since the only characteristic that appears to consistently discriminate between arch types is calcaneal inclination (Harris, R. I., & Beath, T., 1948; Meehan, R. E., & Brage, M., 2003; Roth, S., Roth, A., Jotanovic, Z., & Madarevic, T., 2013), analyzing calcaneal plantar flexion may be a useful method to provide dynamic information of the foot arch during movement. However, a limitation of Okita et al. is that calcaneal plantar flexion was studied in a cadaver model, therefore independent corroboration in vivo is required. The first purpose of this investigation was to describe biomechanically and statistically this rotation of the calcaneus segment during the stance phase of gait. The second purpose of this investigation was to then examine the relationship between these calcaneal rotations and foot arch type during the stance phase of gait.

Methods

Participants

Participants were recruited as a convenience sample from the university community. The study was approved by the University's Research Ethics Board and only participants with at least one foot categorized as being flexible (i.e. non-rigid) were enrolled in the study. Based on pilot research which found calcaneal plantar flexion differences of 5 to 10°, effect size calculations found that 28 participants were necessary for statistical relevance. Fourteen men and sixteen women provided informed consent and participated in the study. All subjects were screened to determine that they had no previous lower limb surgeries nor current injuries which would affect the study.

Longitudinal Arch Angle Measurement

The longitudinal arch angle (LAA) measurement has been previously used to categorize arch types (McPoil & Cornwall, 2005). A static LAA test has been used as an indicator of structural foot arch types in static positions (Cavanagh & Rodgers, 1987; McPoil & Cornwall, 2005). A modified LAA measurement has also been proposed as a measure of functional arch type where the change in LAA is measured between two postures – weight bearing and non-weight bearing -- which is similar to the navicular drop test (Nilsson et al., 2012). For this investigation, the two postures used to measure functional arch type were sitting and standing positions to provide a quasi-static measure representing the change in MLA structure and an indication of functional arch type. Pilot testing found this method was reliable to 1º with a standard deviation of 2º.

To perform the LAA test, the navicular tuberosity, first metatarsal head, and medial malleolus were palpated and marked on both feet. The LAA was measured using a goniometer with the goniometer centered on the navicular tuberosity and the arms aligned with the first metatarsal head and medial malleolus. The LAA measurement was performed three times for each foot while the participant was sitting with no weight on the foot and standing on a single leg with full weight on the foot (Figure 2-1). The LAA measurement in single leg standing was used as the measure of structural arch type. The difference between LAA in sitting and single leg standing was used as the measure of functional arch type. Based on preliminary research and findings in Nilsson et al. (2012), a minimum difference of 5° in LAA between these positions was used to classify potential participants as having a flexible, or non-rigid, arch. Potential participants who had at least one foot classified as a flexible arch were included in the study. Five potential participants were screened but not enrolled in the study due to this criterion.

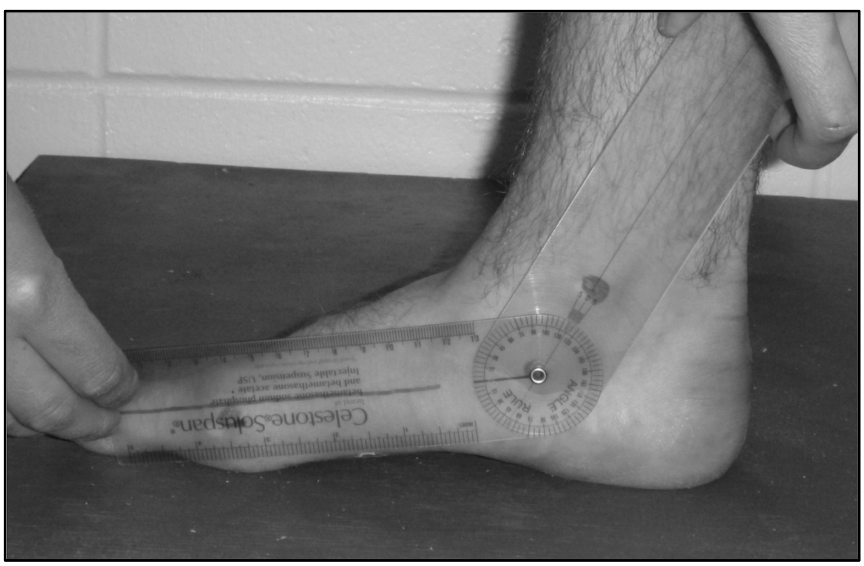


Figure 2-1: Image showing method for measuring LAA. The angle between the medial malleolus, navicular tuberosity, and head of the first metatarsal is measured using a goniometer.

Motion Capture

Motion analysis was performed using a seven-camera optoelectronic motion capture system (Qualisys ProReflex MCU240; Qualisys, Gothenburg, Sweden) and two force platforms (AMTI OR6-6; AMT, Watertown, MA, USA). Motion capture data were sampled at 120 Hz and force platform data were sampled at 1,200 Hz. Force platform data were only used to identify the stance phase of gait. Thirty retro-reflective markers (9 mm) were used to identify important landmarks on the participants' lower limbs. Markers identifying the participants' feet and ankles were placed on the first and fifth metatarsal heads and bases; the medial and lateral malleoli; the medial, lateral and posterior calcaneus; and the medial and lateral tibial plateaus. Additionally, clusters of four markers affixed to a rigid plastic plate were used to track the motion of the shank. All markers were placed on both the right and left sides. After markers were placed on the participant, a standing calibration trial was taken for 10 seconds while the participant stood as still as possible.

For gait trials, the participant's average walking speed was controlled for using laser photogates and only trials within 1.4 ± 0.2 m/s were accepted (Bohannon, 1997; Rose, Ralson, & Gamble, 2006). Gait speed was controlled since faster or slower speeds could result in different calcaneal tendon forces during stance, which could influence the magnitude of calcaneal rotation. Participants were allowed to practice their gait in the laboratory *ad libitum* prior to data collection. Once comfortable with the procedures, participants performed five trials for each foot landing on the force plate. If the foot missed the force plate or the gait speed was outside of the normal range, that trial was performed again. Participants were allowed to perform the trials in any order they wished, to prevent aiming at the force plate with a predetermined foot. Participants took on average approximately eight trials to get five usable trials per foot.

Data Processing

Coordinates of the retro-reflective markers from the gait trials were processed using a right hand coordinate system in Visual 3D (version 4.75.36; C-Motion, Inc, Germantown, MD, USA). All markers were low-pass filtered using a 4^{th} order bidirectional Butterworth with a cut-off frequency of 10 Hz. A Fast Fourier Transform found 95% of the signal for the markers was below 10 Hz. Segments of the lower limb were modeled in Visual 3D to allow for segmental analysis during gait. In Visual 3D, the proximal and distal ends of a segment were defined from the marker data with the longitudinal (Z) axis of the segment running from the proximal to distal end. The segment coordinate system was located at the proximal end of the segment. The medial-lateral axis was defined as the X-axis and the Y-axis is orthogonal to the longitudinal and medial-lateral axes. The Y- and Z-axis values for the left segments were negated to allow the resulting left and right rotation values to have the same anatomical interpretations.

The proximal end of the shank was modeled based on the medial and lateral tibial plateau markers. The distal end of the shank was defined as the midpoint of the medial and lateral malleoli to prevent tibial torsion during gait from affecting the segment rotations. The medial and lateral tibial plateau markers were used to define the orientation of the X-axis with the Y-axis orthogonal to the X- and Z-axes (Figure 2-2). The positive directions of the axes were directed to the right (X), anterior (Y) and superior (Z). Rotations about the X-, Y- and Z-axes corresponded with sagittal, frontal and transverse plane rotations, respectively, with positive rotations indicating extension, adduction and internal rotation. To more easily compare to calcaneal and ankle rotations, sagittal plane rotation of the shank will be described in terms of its effect on the resulting ankle joint rotation. So extension (positive rotation) of the shank is plantar flexion and flexion (negative rotation) of the shank is dorsiflexion.

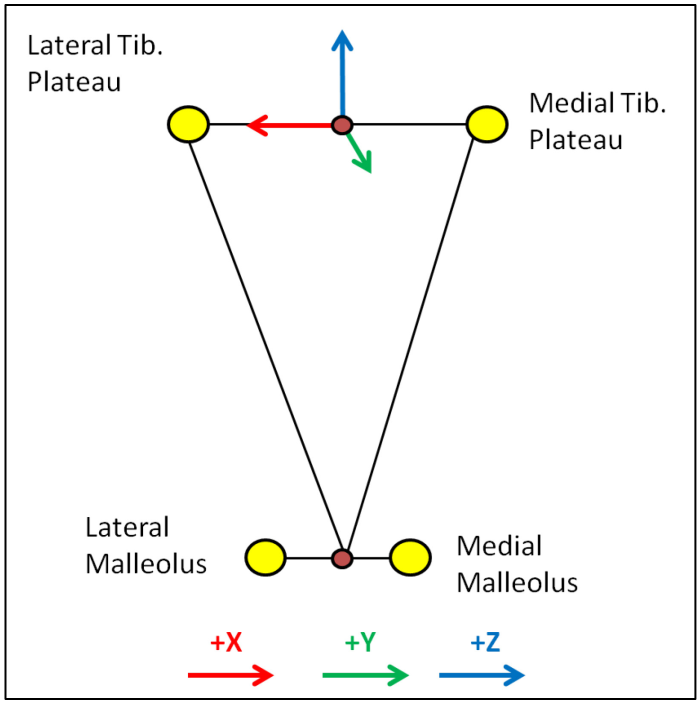


Figure 2-2: Diagram showing the method used for modeling the shank for processing motion analysis data. Yellow circles identify retro-reflective skin markers, red circles identify center points between these markers. This is a frontal plane view of the shank.

The proximal end of the calcaneus was modeled using the posterior calcaneal marker and the distal end of the calcaneus from the mid-point between the medial and lateral calcaneal markers. The medial and lateral calcaneal markers were also used to define the orientation of the X-axis. The positive directions of the axes were directed to the right (X), superior (Y) and posterior (Z) (Figure 2-3). Rotations about the X-, Y- and Z-axes corresponded with sagittal, transverse, and frontal plane rotations, respectively, with positive rotations indicating dorsiflexion, internal rotation and eversion.

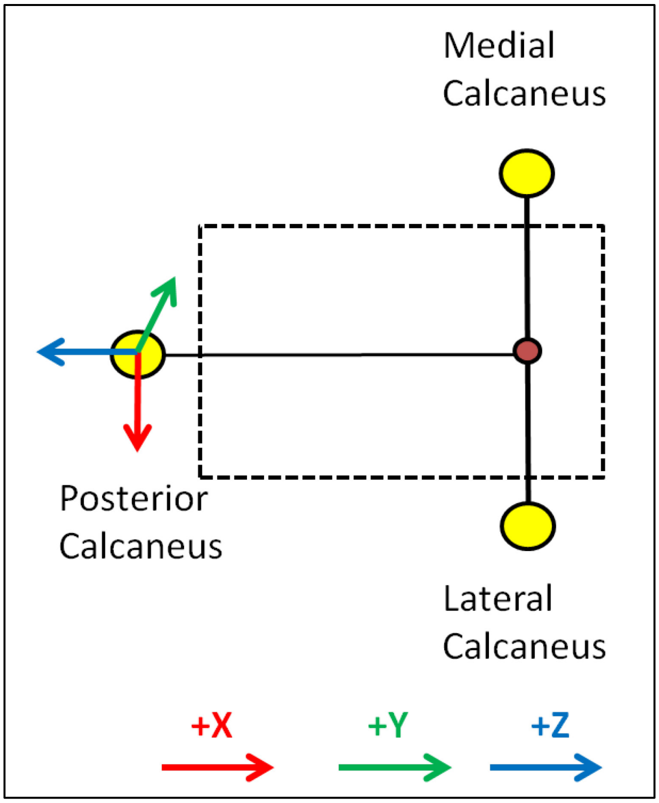


Figure 2-3: Diagram showing method for modeling the calcaneus from motion analysis data. Yellow circles identify retro-reflective markers, red circles identify center points. This is a top down view of the calcaneus.

The forefoot was defined proximally as the mid-point between the bases of the first and fifth metatarsals and distally as the mid-point of the first and fifth metatarsals heads. The positive directions of the axes were directed to the right (X), superior (Y) and posterior (Z). Rotations about the X-, Y-, and Z-axes corresponded with sagittal, transverse, and frontal plane rotations. The forefoot was only used to identify events during stance.

Rotations of the shank and calcaneus segments were calculated using a ZYX Cardan sequence using the lab coordinate system as the reference. Ankle joint angle was calculated using an XYZ Cardan sequence using the shank as the moving segment and the calcaneus as the reference segment.

Significant temporal events were identified in Visual 3D to allow for analysis of segmental and joint rotations at and between those specific time points. The stance phase of gait was identified based on force platform data. Heel strike was identified at the point in time where the vertical ground reaction force increased above zero, while toe-off was when the vertical ground reaction force decreased to zero.

Stance phase data was temporally normalized to stance time (i.e. 0-100% stance). During stance, both foot flat and heel-off were identified based on kinematic marker data. Foot flat was identified as the frame where the vertical displacement of the fifth metatarsal head plateaued. This event identifies the initial time where the forefoot contacts the ground. The time between heel strike and foot flat was operationally defined as early stance. At foot flat, ground reaction force may be applied at both ends of the MLA, therefore inter-segmental foot motion may occur and the MLA may begin to deform, including plantar flexion of the calcaneal. Heel off was identified as the frame where the vertical velocity of the calcaneus increased above zero after foot flat had occurred. At heel-off the rearfoot leaves the floor, therefore ground reaction force is no longer applied to the rearfoot. The time from foot flat to heel-off was operationally defined as the midstance portion of gait. Change in calcaneal angle in the sagittal and frontal planes from the start to end of midstance were measured. Specifically, calcaneal plantar flexion excursion (i.e. sagittal plane) and calcaneal eversion excursion (i.e. frontal plane) were determined.

Visual 3D was used to determine the sagittal plane angle of the shank, calcaneus, and ankle at these events. The ankle angle was used to compare the results of this study to previously performed research since sagittal plane ankle angle is more commonly measured than independent angles of the shank and calcaneus. Ankle angles were also measured from foot flat to heel off.

Statistical Analyses

The first purpose of this investigation was to biomechanically and statistically describe rotation of the calcaneus during the stance phase of gait. Descriptive statistics (mean and standard deviation) were used to describe calcaneal plantar flexion and eversion excursion during midstance. In addition, the mean and standard deviation of the participants' age, height, weight, foot length, LAA and change in LAA were determined. Quantile-quantile (Q-Q) plots were used to describe the distribution of the LAA, change in LAA, calcaneal plantar flexion excursion, and calcaneal eversion excursion.

The second purpose of this investigation was to examine the relationship between foot arch types and calcaneal rotations during midstance. Pearson product moment correlations were used to determine the relationship between structural arch type (LAA) with calcaneal plantar flexion and eversion excursions and between functional arch type (change in LAA) with calcaneal plantar flexion and eversion excursions.

Results

Descriptions

Fourteen men and sixteen women were recruited to participate in the study. Each participant was initially screened to exclude participants with any previous lower limb surgeries or injuries that would affect the study. Anthropometric measurements were taken for each participant including height, mass, and age (Table 2-2). The length of each foot was also measured using broad-blade anthropometric calipers.

Table 2-2: Anthropometric Data for Participants included in this Study

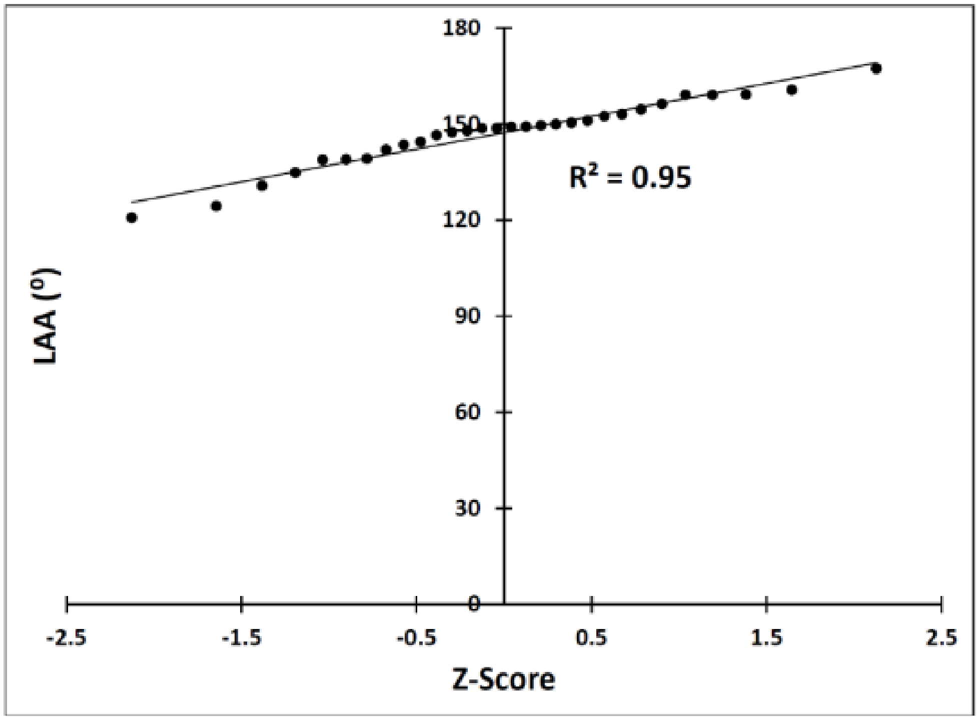
	Women	Men
Height (m)	1.65 ± 0.11	1.76 ± 0.05
Body Mass (kg)	65.9 ± 7.9	83.1 ± 19.1
Age (years)	24.9 ± 3.0	25.8 ± 4.1
Right Foot Length (cm)	23.7 ± 1.2	25.7 ± 1.1
Left Foot Length (cm)	23.6 ± 1.2	25.6 ± 1.1

The average height of men participants was 1.76 ± 0.05 m and women participants were 1.65 ± 0.11 m. Men's and women's body mass were 83.1 ± 19.1 kg and 65.9 ± 7.9 kg, respectively. Men's left and right feet were 25.6 cm ± SD and 25.7 cm ± SD long, respectively. Women's left and right feet were 23.6 cm ± SD and 23.7 cm ± SD long, respectively.

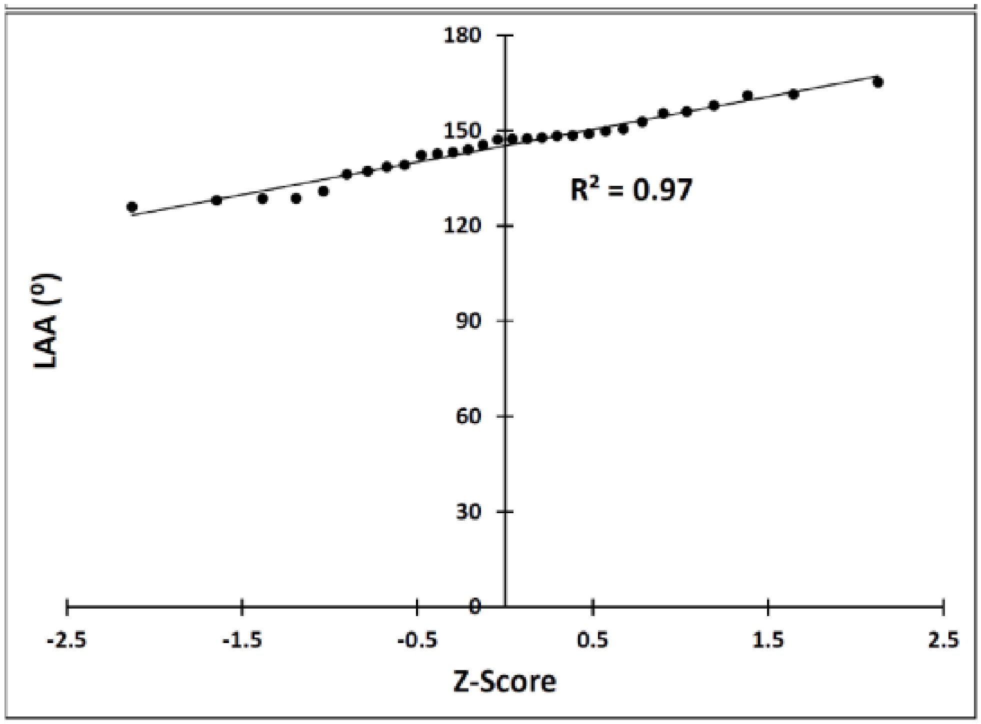
LAA at non-weight bearing, LAA at weight bearing, and the difference between the two were measured for both feet for all participants (Table 2-3). The distribution of the LAA measurement at weight bearing (Figure 2-4) and the change in LAA (Figure 2-5) were analyzed using Q-Q plots. Means and standard deviations of the data showed that few data points were outside of one standard deviation from the mean with the range barely being larger than one standard deviation away from the mean. Analysis of the Q-Q plots showing distributions of both the LAA at weight bearing and the change in LAA identified normally distributed results. High R^2 values also indicated a high linearity of the data.

Table 2-3: Mean and Standard deviations for LAA Measurements

	Left	Right
LAA – Non-Weight Bearing	153 ± 12°	150 ± 12°
LAA – Weight Bearing	147 ± 6°	145 ± 10°
LAA Change	6 ± 4°	5 ± 4°

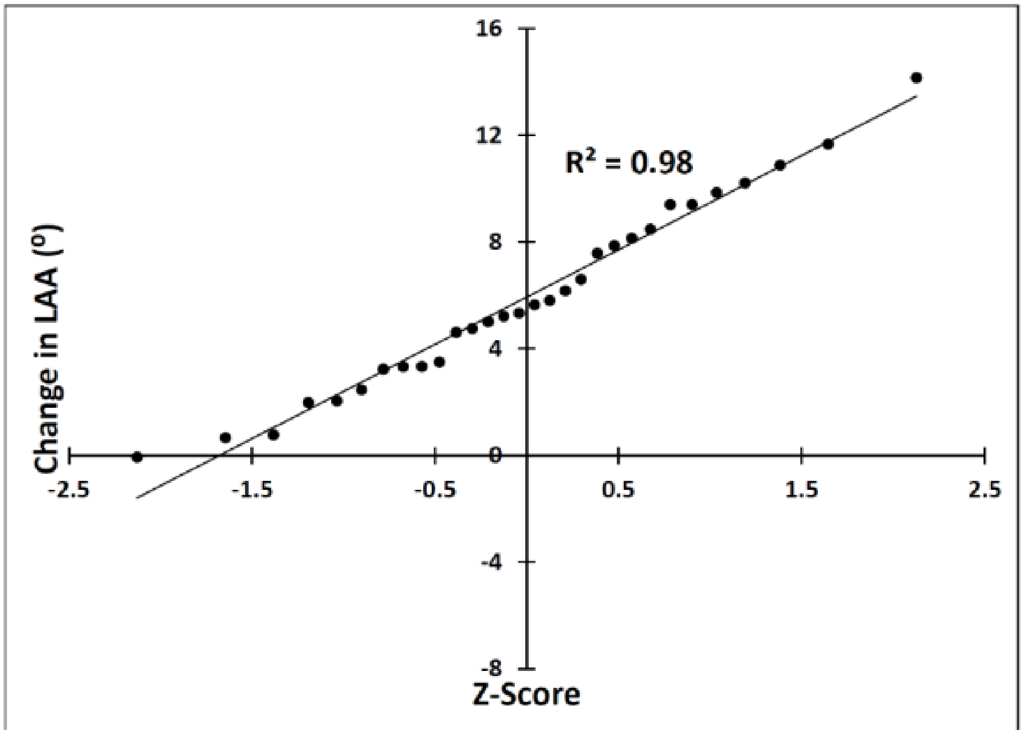


a.

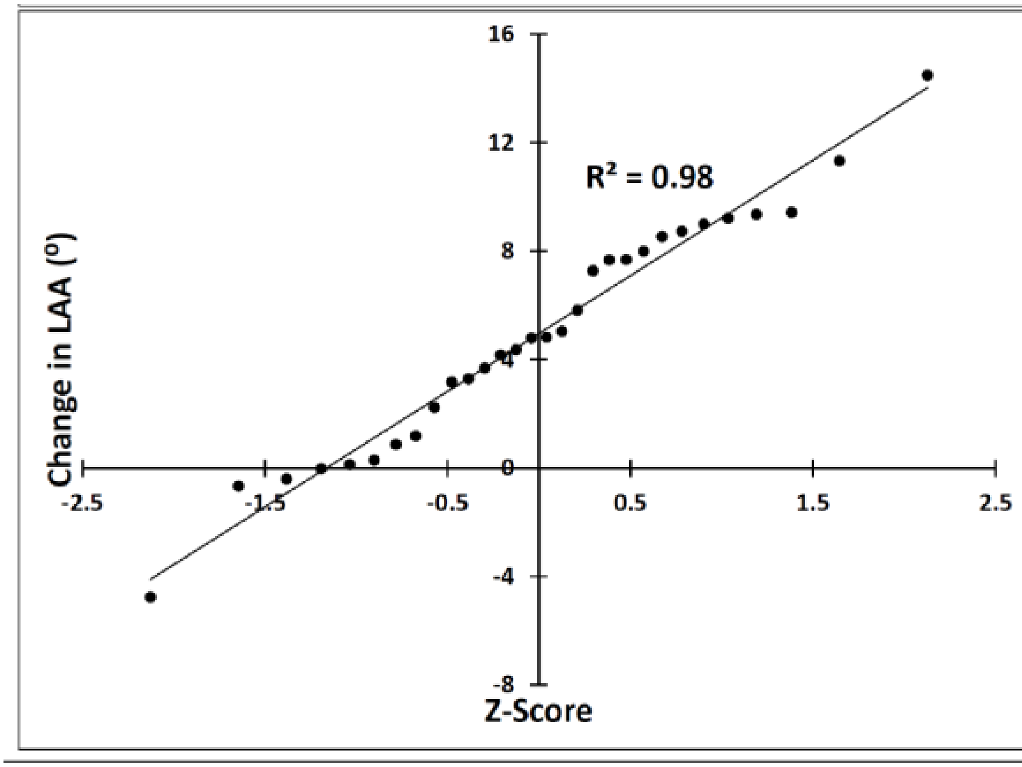


b.

Figure 2-4: Q-Q Plots showing distribution of LAA at weight bearing for both the left (a) and right (b) feet. A Z-score of zero is the mean of the data, with increasing Z-score moving away from the mean. A Z-score of ±1 indicates one standard deviation away from the mean. The linearity of the resulting line of points identifies how normally distributed the data set is, more linearity equates to more normally distributed.



a.



b.

Figure 2-5: Q-Q plots showing the distribution of the LAA change from non-weight bearing to weight bearing for both the left (a) and right (b) feet. A Z-score of zero is the mean of the data, with increasing Z-score moving away from the mean. A Z-score of ±1 indicates one standard deviation away from the mean. The linearity of the resulting line of points identifies how normally distributed the data set is, more linearity equates to more normally distributed.

Joint and segment angles through the stance phase of gait were also analyzed for each participant. The resulting graph of a participant (Figure 2-6) during stance is representative of typical rotations occurring during stance. Angles were compared from heel strike to foot flat to heel off. Average angles for the ankle joint, shank segment, and calcaneus segment were also calculated for both early and mid-stance where early stance is from heel strike to foot flat and midstance is from foot flat to heel off (Table 2-4).

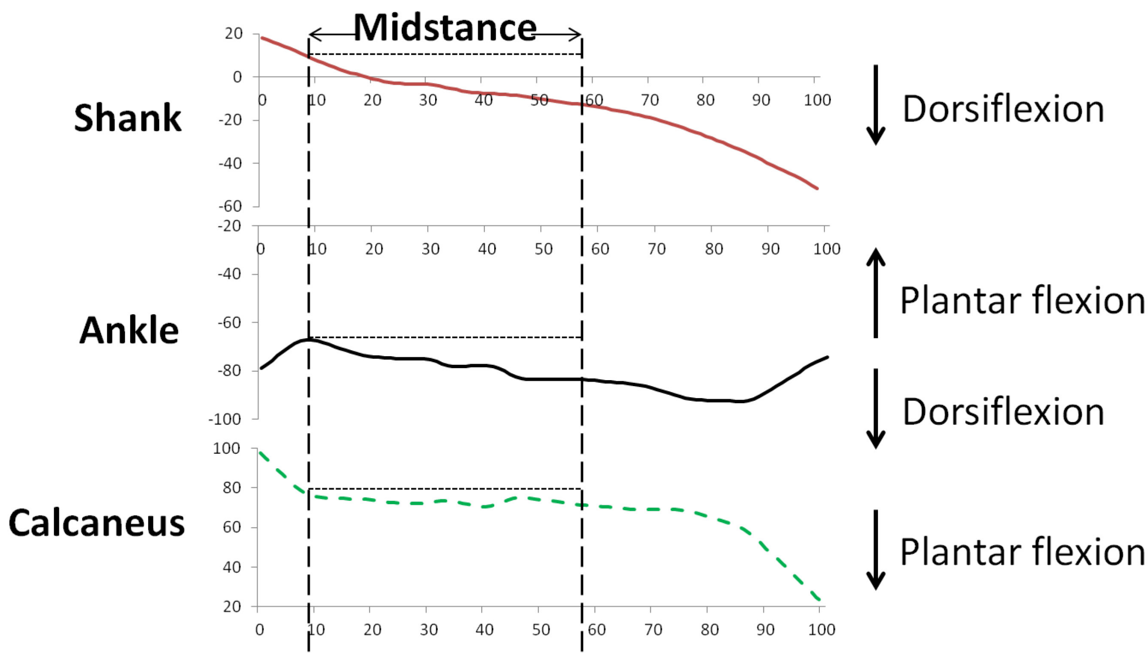


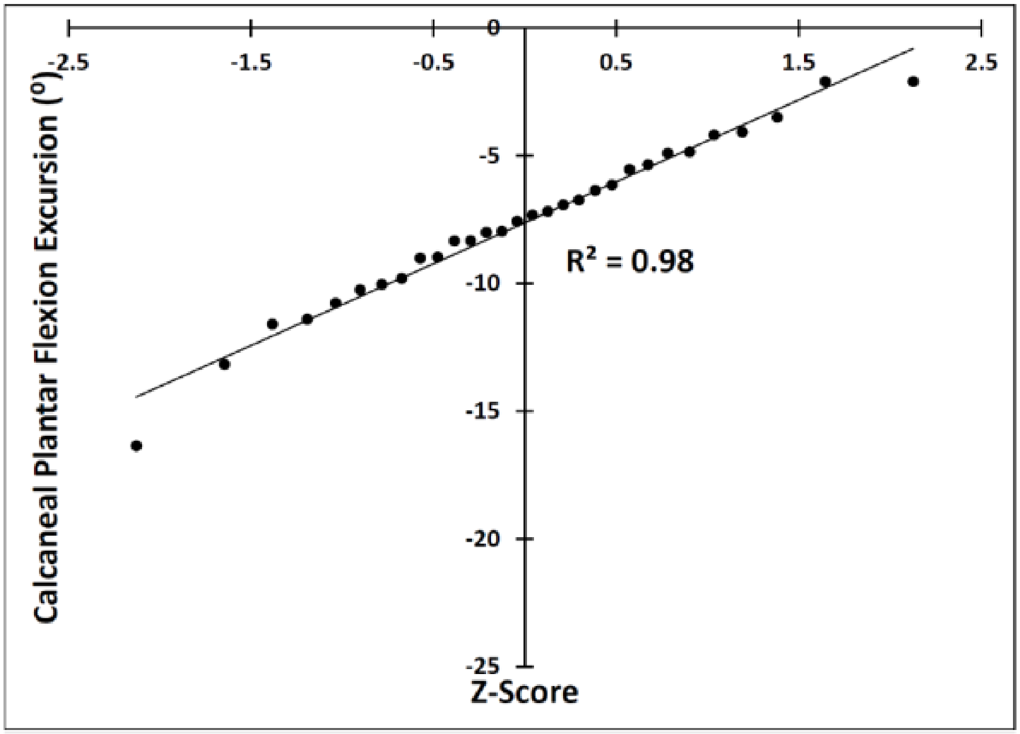
Figure 2-6: Graph showing ankle, shank, and calcaneal angles during stance for a representative participant. Rotations of the individual segments can be identified based on their change during midstance.

Table 2-4: Mean and Standard Deviations of Joint and Segment Angle Excursions during Early and Mid-Stance Phases of Gait.

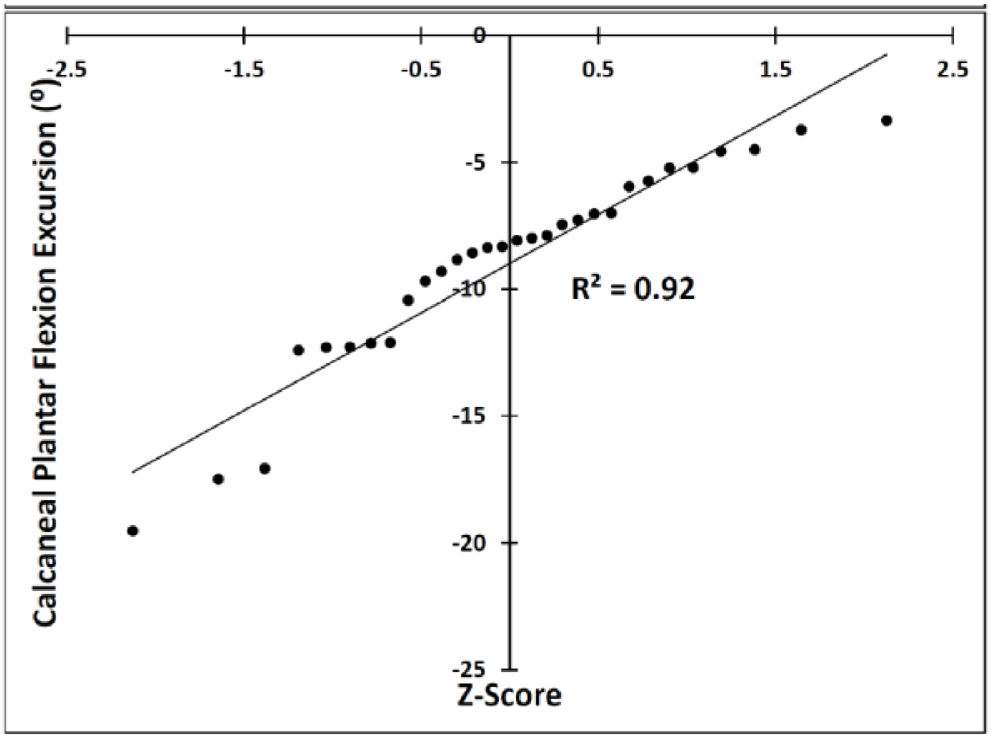
	Left			**Right**		
	Ankle	Shank	Calcaneus	Ankle	Shank	Calcaneus
Early Stance	23.4 ± 6.4°	-7.1 ± 2.6°	-16.3 ± 4.6°	20.7 ± 6.2°	-5.9 ± 1.8°	-15.5 ± 4.2°
Midstance	-13.2 ± 3.4°	-20.7 ± 3.6°	-7.6 ± 3.2°	-13.5 ± 3.8°	-22.4 ± 2.8°	-9.0 ± 4.0°

During early stance, the ankle was seen to plantar flex, which corresponds to the calcaneal plantar flexion also occurring. The calcaneal plantar flexion excursion during this period of stance was greater than the shank dorsiflexion, allowing calcaneal plantar flexion to dominate the resulting measured ankle rotation during early stance. However, during midstance, ankle dorsiflexion starts to occur. This corresponds with the shank dorsiflexion occurring during this period. Since the shank dorsiflexion is much larger than the calcaneal plantar flexion also occurring, the ankle joint rotation is measured as dorsiflexing, with shank rotation dominating ankle rotation during this period. Due to the greater amount of shank dorsiflexion during midstance, an ankle joint rotation measurement is not able to identify the calcaneal plantar flexion which is also occurring.

The distribution of calcaneal excursion during midstance was also analyzed using Q-Q plots (Figure 2-7). This showed relatively high linearity of both the left (R^2 = 0.98) and right feet (R^2 = 0.92), with the right foot having less linearity than the left foot. Both feet were normally distributed. The data values are centered close to the mean ± one standard deviation with few data points being outside one standard deviation from the mean.



a.



b.

Figure 2-7: Q-Q plots showing calcaneal plantar flexion excursion during midstance for the left (a) and right (b) feet. A Z-score of zero is the mean of the data, with increasing Z-score moving away from the mean. A Z-score of ±1 indicates one standard deviation away from the mean. The linearity of the resulting line of points identifies how normally distributed the data set is, more linearity equates to more normally distributed.

Inferential Statistics

Pearson product moment correlations were used to assess the relationship between calcaneal plantar flexion and eversion excursions during midstance with LAA at weight bearing, representing structural arch type, for both the left and right feet (Table 2-5). Calcaneal plantar flexion excursion during midstance was significantly correlated with left LAA at weight bearing, however not with right LAA at weight bearing. Neither the left nor right LAA at weight bearing correlated with calcaneal eversion excursion during midstance. Differences between right and left feet may just be due to the small sample size or could indicate overarching differences between sides.

Table 2-5: Pearson Product Moment Correlation Results Comparing Calcaneal Excursion during Midstance and Structural Arch Type

	Left LAA Weight Bearing	Right LAA Weight Bearing
Calcaneal Plantar Flexion Excursion during Midstance	r = -0.48; p = 0.007	r = -0.14; p = 0.461
Calcaneal Eversion Excursion during Midstance	r = 0.02; p = 0.916	r = -0.34; p = 0.066

Pearson product moment correlations were also used to assess the relationship between calcaneal plantar flexion and eversion excursions during midstance to the change in LAA, representing functional arch type, for the left and right feet (Table 2-6). None of these correlations were found to be statistically significant.

Table 2-6: Pearson Product Moment Correlation Results for Calcaneal Excursions during Midstance compared to Functional Arch Type

	Left LAA Change	Right LAA Change
Calcaneal Plantar Flexion Excursion during Midstance	r = 0.07; p = 0.713	r = -0.08; p = 0.674
Calcaneal Eversion Excursion during Midstance	r = -0.27; p = 0.149	r = 0.12; p = 0.528

Only one statistically significant correlation was found when comparing calcaneal excursions during midstance and either structural or functional arch types. This could be due to interaction of structural and functional foot types and the variety of each type found within the study. Structural and functional foot types were not found to be related to each other, with no correlations found (Table 2-7). One example of this interaction is a participant with a structurally normal (LAA = 144°) yet a functionally flexible foot with the most calcaneal plantar flexion measured (Calcaneal plantar flexion excursion = 19.5°) (Figure 2-8).

Table 2-7: Pearson Product Moment Correlation Results Comparing Functional and Structural Arch types

	Left LAA Change	Right LAA Change
LAA at Weight Bearing	r = 0.22; p = 0.243	r = 0.24; p = 0.201

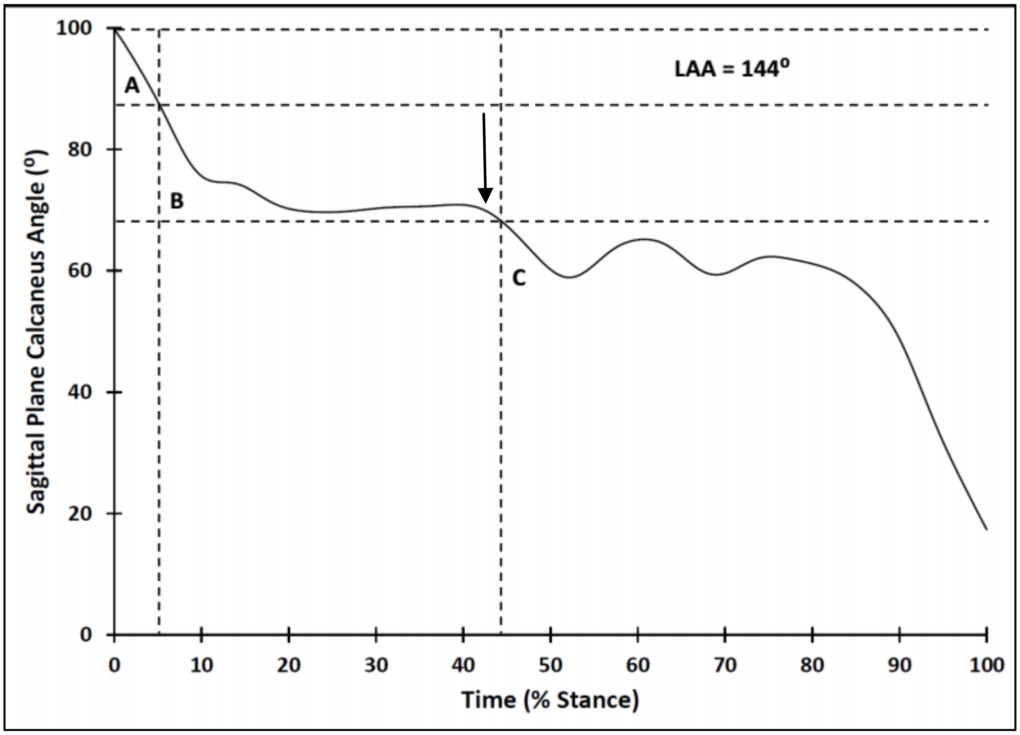


Figure 2-8: Calcaneal plantar flexion during stance for a participant with LAA of 144°. Time point A is heel strike, B is footflat, and C is heel off; midstance is between B and C.

Though the participant with the largest calcaneal plantar flexion excursion during midstance had close to a median LAA, participants with the highest and lowest LAA had relatively low calcaneal plantar flexion excursions during midstance. The participant with the largest LAA (165°) only had 4.6° of calcaneal plantar flexion excursion during midstance, indicating a structurally pes cavus and a functionally more rigid foot (Figure 2-9). The participant with the smallest LAA (126°) also had a low amount of calcaneal plantar flexion excursion during midstance (5.7°), indicating a pes planus structural foot yet a functionally more rigid foot as well (Figure 2-10). Note that truly rigid feet were excluded from this study, so a foot with low calcaneal plantar flexion excursion during midstance may not be at the true end of the spectrum.

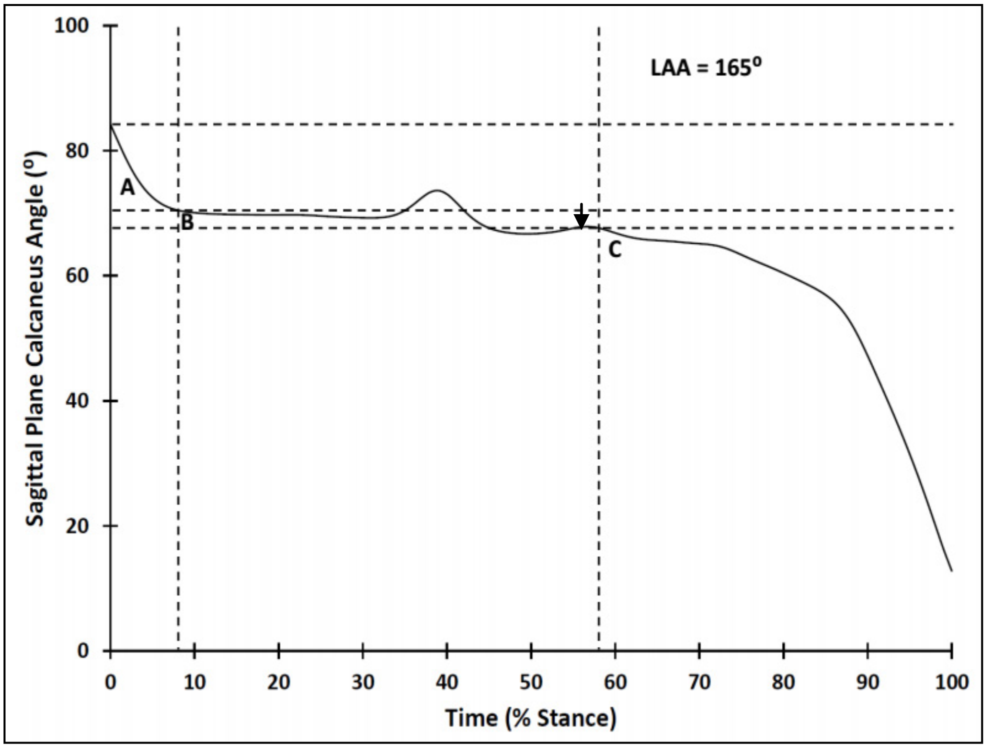


Figure 2-9: Calcaneal plantar flexion during stance for the foot with the highest LAA (165°). Time point A is heel strike, B is footflat, and C is heel off; midstance is between B and C.

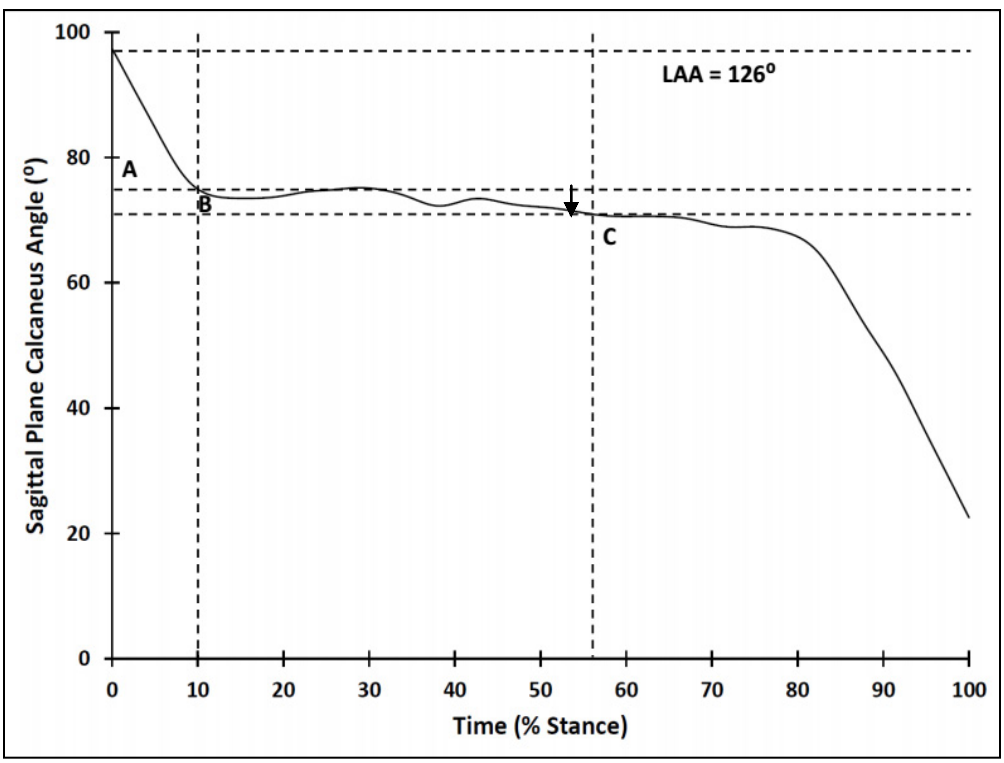
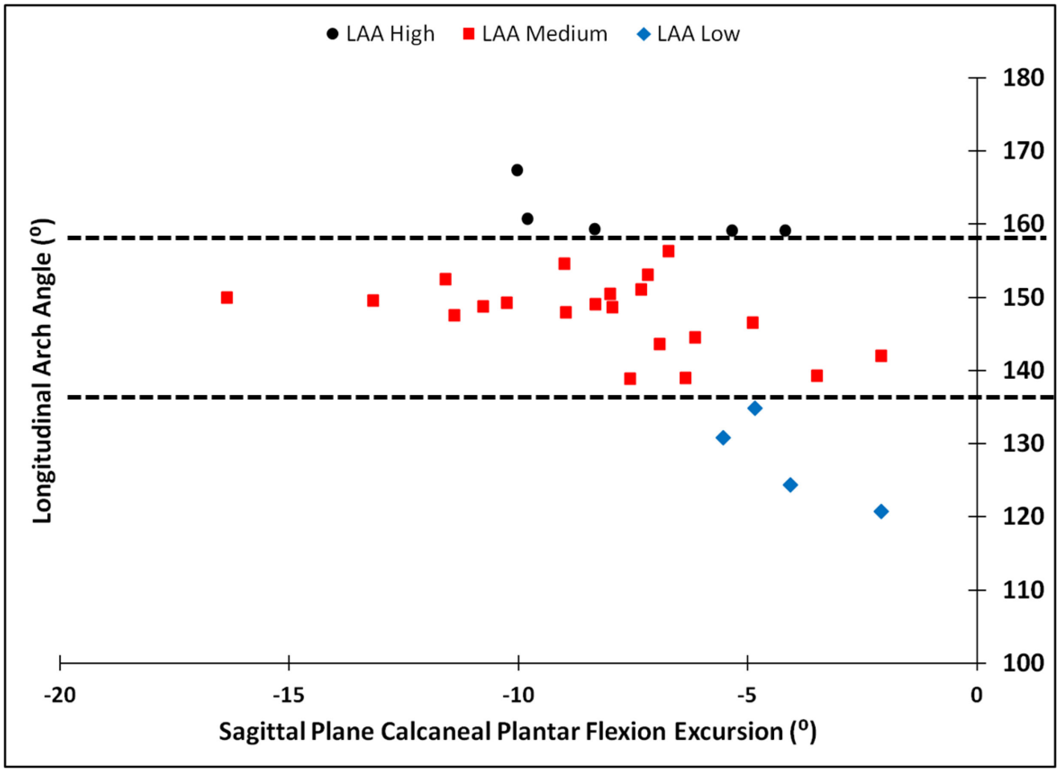
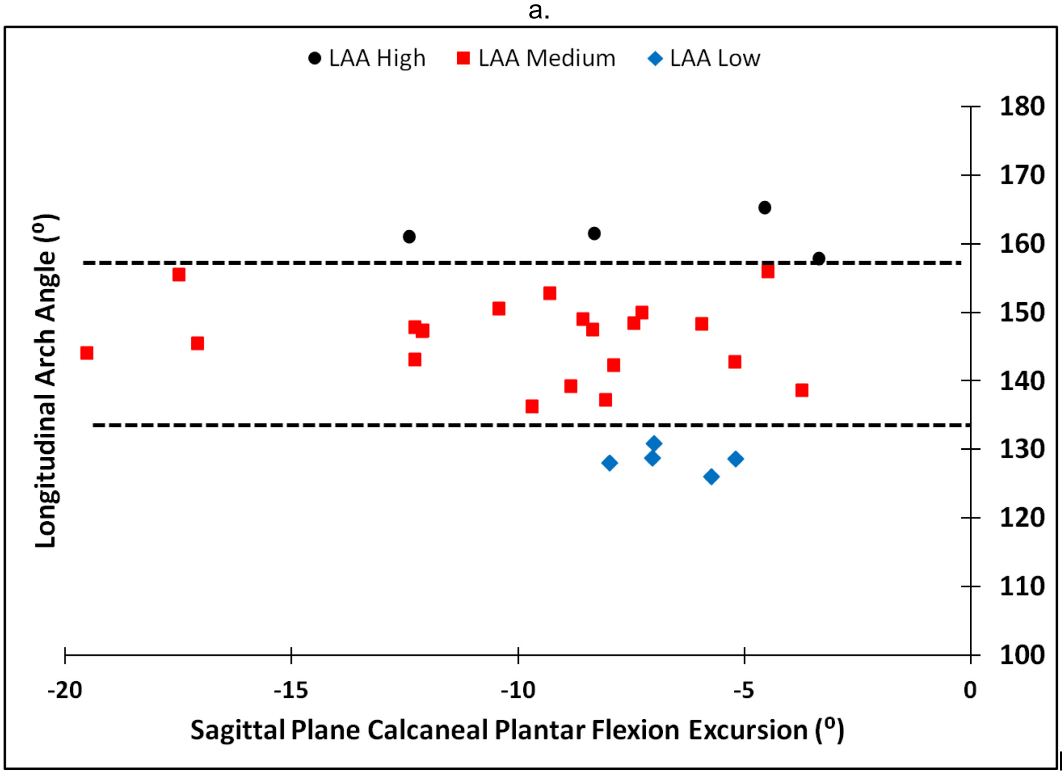


Figure 2-10: Calcaneal plantar flexion during stance for the foot with the lowest LAA (126°). Time point A is heel strike, B is footflat, and C is heel off; midstance is between B and C.

Based on the LAA at weight bearing, participants' feet can be grouped into structural arch type categories. Consistent with prior studies (Jonson & Gross, 1997; McPoil & Cornwall, 2005) these categories were assigned based on the mean ± one standard deviation since no distinct groups have been identified. For this study, a normal foot had a LAA of between 141° and 153° (mean ± 1 SD). A pes planus foot was any foot with a LAA less than 141°, and a pes cavus foot had a LAA greater than 153°. Once grouped, the LAA was then compared to calcaneal plantar flexion excursion (Figure 2-11).



a.



b.

Figure 2-11: LAA versus calcaneal plantar flexion excursion during midstance based on structural arch groups for left (a) and right (b) feet. Structural arch types were grouped where one standard deviation away from the mean indicates a high or low arch.

Analysis of calcaneal plantar flexion excursion during midstance based on structural arch groups shows a wide variety of excursions between groups. Feet categorized as pes planus types had low calcaneal plantar flexion excursion during midstance, while pes cavus foot types had low to moderate calcaneal plantar flexion excursion during midstance. Though these groups seemed to group together, feet categorized as structurally normal feet had a wide range of calcaneal plantar flexion excursion during midstance, from close to the lowest to the highest amount of excursion found for either foot.

Discussion

Analysis of Calcaneal Rotations

Compared to previous studies, ankle joint rotations for the stance phase of gait were found to be similar (Leardini et al., 2007; Moseley et al., 1996). Leardini et al. found ankle joint dorsiflexion during midstance to be approximately 15°, similar to the 13° of dorsiflexion found in this study (Leardini et al., 2007). Since ankle joint rotations during early and mid-stance were found to be comparable to previous research, calcaneal and shank segment rotations should also be consistent had they been previously reported. The calcaneus and shank segments were found to rotate in the same direction during both early and mid-stance, plantar flexion and dorsiflexion, respectively. Yet the amount of rotation occurring at each segment changed during the phases, resulting in different contributions to ankle joint rotation.

The measured ankle joint rotation (plantar flexion) during early stance reflects the large calcaneal plantar flexion during this phase. The greater rotation of the calcaneus during early stance overshadows the smaller dorsiflexion of the tibia, resulting in measured ankle joint plantar flexion. Yet during the midstance phase, tibial dorsiflexion surpasses calcaneal plantar flexion, resulting in measured ankle joint dorsiflexion. By only measuring ankle joint rotation, previous studies have been unable to identify the calcaneal plantar flexion during this phase.

Okita et al. (2013) previously found calcaneal plantar flexion during stance, however in cadavers during simulated gait (Okita, N., Meyers, S. A., Challis, J. H., & Sharkey, N. A., 2013). The findings from this study support the results of Okita et al. during *in vivo* gait. In particular, the time-series figures of sagittal plane calcaneal rotation during stance appear qualitatively and quantitatively similar between the current study and those reported in Okita et al. Chizewski & Chiu also found calcaneal plantar flexion during a standing squat (Chizewski & Chiu, 2012). Resulting calcaneal plantar flexion rotations found during midstance in this study were similarly to those found by Chizewski and Chiu, ranging from 5 to 20° and 5 to18° respectively (Chizewski & Chiu, 2012). Taken together, these studies find the range of calcaneal plantar flexion during weight bearing to be consistent, which indicates that calcaneal plantar flexion during weight bearing is a real phenomenon.

Calcaneal plantar flexion found during mid-stance could be key in analyzing MLA deformation during stance. During stance a "reverse" Windlass mechanism occurs, where the MLA flattens, the plantar fascia tightens and the metatarsalphalangeal joint is pulled into plantar flexion. This flattening of the MLA is caused by the foot moving into full weight bearing. During mid-stance calcaneal plantar flexion may also reflect this MLA deformation. Though sagittal plane calcaneus segment rotation is rarely looked at independently during gait, it has been shown to have a lower inclination (plantar flexion) during weight bearing for people with "flatfoot" (Meehan & Grage; Van Boerum & Sangeorzan; Ross et al, Harris & Beath). Therefore, sagittal calcaneal rotation during mid-stance may be related to MLA differences and rotations. Previous research which has compared MLA differences to calcaneal inclination has done a poor job of describing structural and/or functional foot differences, or even in distinguishing between the two. Since accurate analysis of MLA differences is rarely performed, this has led to unpredictable results correlating calcaneal rotations with MLA.

Calcaneal Rotation during Midstance and Structural Foot Arch Types

A possible relationship between calcaneal plantar flexion during midstance and structural arch type was found, but only in the left foot. This correlation indicated a lower structural MLA was associated with less calcaneal plantar flexion excursion during midstance. No other calcaneal excursions during midstance were found to correlate with structural arch type. On the surface, these results suggest that no relationship exists between structural foot arch type and calcaneal rotation during midstance. However, when examining the scatterplots describing weight bearing LAA and calcaneal plantar flexion during midstance, an interesting observation was made. Specifically, the range of calcaneal plantar flexion during midstance appeared to be clustered in specific patterns for low, moderate and high weight bearing LAA. To explore this observation, participants were grouped into structural arch type categories.

Using this descriptive statistics based classification, four left and five right feet were considered pes planus; 21 left and 21 right feet were considered normal; and five left and four right feet were considered pes cavus. This distribution is comparable to those reported in previous studies categorizing feet based on structural arch type (E. J. Harris et al., 2004). The absolute range for calcaneal plantar flexion during midstance was -2 to -20° in right feet. The range of calcaneal plantar flexion during midstance for participants categorized as pes planus was -2 to -8°. Therefore, pes planus feet had relatively small calcaneal plantar flexion excursions. The range of calcaneal plantar flexion during midstance for participants categorized as pes cavus was -3 to -12°. Therefore, pes cavus feet had calcaneal plantar flexion excursions during midstance that were relatively small to moderate. The range of calcaneal plantar flexion during midstance for participants categorized as normal was -2 to -20°. Thus, normal feet ranged from relatively small to relatively large plantar flexion excursions during midstance. These different ranges for pes planus, normal, and pes cavus categorized feet suggests the amount of calcaneal plantar flexion during midstance occurring is dependent on structural foot arch type.

Pes planus feet were found to have small calcaneal plantar flexion excursions during midstance. Previous research has found a lower calcaneal inclination measured using radiography during standing; similar to the position the weight bearing LAA was measured. If the calcaneus is already oriented in plantar flexion in pes planus feet, further plantar flexion during midstance would be minimized as the anterior portion of the calcaneus would be close to contacting the ground. Therefore, calcaneal plantar flexion during midstance is likely limited by bony shape.

Pes cavus feet had a larger range of calcaneal plantar flexion excursion during midstance. In contrast to pes planus feet, a pes cavus foot should have a greater calcaneal inclination, thus a larger plantar flexion excursion during midstance would be possible. This suggests calcaneal plantar flexion excursion during midstance is limited by soft tissue extensibility. These soft tissues could include the calcaneonavicular ligament and the plantar fascia. Therefore, a pes cavus foot with relatively small calcaneal plantar flexion excursion during midstance would have poor extensibility of these soft tissues, whereas a pes cavus foot with moderate calcaneal plantar flexion excursion during midstance would have greater soft tissue extensibility.

Feet categorized as normal structural arch types had the widest range of calcaneal plantar flexion excursions during midstance. As calcaneal inclination is greater for normal than pes planus feet, bony shape should provide less restriction to calcaneal plantar flexion during midstance, which is observed in the greater plantar flexion excursions during midstance observed. Therefore, normal feet may be similar to pes cavus feet, in that calcaneal plantar flexion during midstance is limited by soft tissue extensibility. However, in contrast to pes cavus feet, greater calcaneal plantar flexion excursion during midstance is observed in normal feet, suggesting normal feet may also have more extensible soft tissues.

Based on the possible effect of soft tissues on calcaneal plantar flexion excursion during midstance, calcaneal plantar flexion during midstance could be an indicator of functional arch type. Furthermore, the possible functional arch types are dependent on the structural arch type classification. In particular, not all functional arch types are observed in pes planus and pes cavus feet. Based on the results from this study, the possible combinations of structural and functional foot arch types were determined (Table 2-8). All three types of structural arch type could be functionally rigid. Structurally pes cavus arch types could also be functionally flexible. Feet with normal structural arch types could be functionally rigid, flexible, or extremely flexible. A limitation of this two-way classification is that participants were required to have at least one foot that demonstrated a change in LAA between weight bearing and non-weight bearing. Thus, extremely rigid or immobile functional arch types may have been excluded. However, this study did have participants with no change in LAA between weight bearing and non-weight bearing, as it was not required that both feet demonstrate a change. Thus, some feet included in the analyses may represent the extremely rigid functional foot arch type.

Table 2-8: Examples of Structural and Functional Arch Types Found in Study

Functional Arch Type	**Pes Cavus**	**Normal**	**Pes Planus**
Most Rigid	Excluded from study, but highly possible		
Rigid	X	X	X
Flexible	X	X	
Most Flexible		X	

Calcaneal Rotations and Functional Arch Types

No correlations were found between functional arch type and either calcaneal plantar flexion or eversion excursions during midstance. This could be due to a lack of a relationship between calcaneal rotation during midstance and functional foot type or due to the methods for measuring functional arch type. Both the weight bearing and non-weight bearing positions for LAA were measured statically yet compared to calcaneal excursion during midstance. Since the calcaneus is the insertion of the calcaneal tendon, in which tension affects the MLA (Cheng et al., 2008), the amount of force in the calcaneal tendon during the functional arch type measurement may be important. During standing, force on the calcaneal tendon is no greater than the body weight on the individual, yet during gait it increases to up to 3.9 times their body weight (Giddings, V. L., Beaupre, G. S., Whalen, R. T., & Carter, D. R., 2000). By measuring functional arch type during standing, maximal arch deformation may not have occurred due to the low calcaneal tendon force. Therefore, the lack of correlation with calcaneal excursion during midstance may have been due to the method for measuring functional arch type.

Since calcaneal tendon forces change based on activity, maximal rotation of the calcaneus may also change for activity. Tasks which require more calcaneal tendon force may also cause more calcaneal plantar flexion. This calcaneal plantar flexion in turn may be resisted, or allowed, by the tension in the plantar fascia. If a foot has a tighter plantar fascia, less calcaneal rotation may be allowed compared to a foot with a looser plantar fascia. The amount of tension in the plantar fascia may be due to foot type and is inherent in the individual (Arangio, G. A., Chen, C., & Salathé, E. P., 1998). Due to this connection between arch deformation, functional arch movement, and calcaneal tendon tension, functional arch type determination may be task specific, requiring functional arch type to be assessed separately for each task an individual performs.

Conclusion

Analysis of calcaneal segment rotation compared to ankle joint rotation during the midstance phase of gait showed that calcaneal plantar flexion may be overshadowed when measuring just ankle joint rotations. Independent analysis may be necessary to determine movements of individual bones in the feet (in particular the calcaneus) during midstance. The amount of this calcaneal plantar flexion excursion during midstance may be different based on structural arch type. If an individual's structural arch type is determined based on LAA, the possible calcaneal plantar flexion excursions during midstance can be determined. By grouping based on structural arch type, calcaneal plantar flexion excursion during midstance may also reflect possible functional arch deformation. Finally, due to the possible variability of functional arch type with task, calcaneal plantar flexion excursion during midstance should be studied in tasks with higher calcaneal tendon forces.

Chapter 3 : General Discussion and Conclusions

By measuring calcaneal excursions as individual segment rotations rather than as a joint rotation between the calcaneus and the tibia, this study was able to identify the rotations of the calcaneus during midstance, as well as compare them to structural and functional arch types. Calcaneal plantar flexion during midstance significantly correlated with structural arch type (for the left foot only) though not with functional arch type. Calcaneal eversion during midstance was not found to correlate with either functional or structural arch type as is traditionally found. This differed from previous research, but was expected since the ankle joint rotations traditionally measured were not used in this study. When ankle joint rotations have been measured, the calcaneal eversion which is correlated to arch type may actually have been shank inversion during midstance rather than calcaneal segment rotation. By measuring independent segment rotation, instead of measuring the rotations of the tibia, the rotations of the calcaneus during midstance were able to be measured. Because previously unidentified rotations were found using this methodology, previous research should be reanalyzed with this method to determine if more information could identified.

Injuries

Research into sports injuries have looked at the effect of foot arch type on injury rates. Studies which have analyzed the effect of foot arch type on injury rates have only measured the foot in a static position, preventing researchers from distinguishing between different functional foot types (Burns et al., 2005; Williams Iii et al., 2001). Measuring plantar flexion of the calcaneus during midstance may be one method for determining the functional foot type of the athletes. A quick method for measuring this rotation would need to be determined, but this would allow researchers to better categorize foot types and possibly find more definitive relationships with injury rates. However, there are two limitations associated with measuring calcaneal plantar flexion. These include determining the neutral position of the calcaneus and identifying the force on the calcaneal tendon during each task. To improve the practical utility of calcaneal plantar flexion measurements, these limitations should be investigated in future studies. Specifically, movements involving calcaneal tendon forces greater than those in gait should be considered, as calcaneal tendon forces directly influence calcaneal plantar flexion. By determining calcaneal plantar flexion during different activities, foot arch types could be related to activity specific injuries.

Injury rates have also been compared to maximum ankle joint dorsiflexion and plantar flexion. This research has found inconclusive and inconsistent results (Iwanuma et al., 2011), possibly due to inaccurate measurements. Measuring segmental rotation of both the shank and calcaneus may allow for more precise identification of rotations occurring and provide better results in correlating to injury rates.

Shoe Types

Identifying calcaneal plantar flexion excursion during midstance as a possible link in distinguishing between arch types, rather than calcaneal eversion, could have implications in athletic shoe design. Currently two categories of athletic shoes are typically made, neutral shoes and stability shoes. A neutral shoe has the same foam underfoot throughout the entire shoe while a stability shoe has a “medial posting” on the medial side of the rear- to midfoot of the shoe. This medial posting is made of a higher density foam which is aimed at limiting rearfoot eversion and arch deformation from excessive pronation during early to midstance phases of athletic activities. A stability shoe is designed for an athlete who has an overpronating foot, which is associated with calcaneal eversion. In the athletic shoe community, calcaneal eversion and overpronation are synonymous with flexible flatfoot. Yet in this study calcaneal eversion was not found to be related to functional or structural foot arch type and was not shown to be indicative of a flexible flatfoot.

No relationship between calcaneal eversion and flexible flatfoot may explain why shoes which have a medial posting and are proposed to prevent overpronation and overpronation-related injuries have been shown to make no difference on injury rates based on foot arch type (McKenzie, D. C., D. B. Clement, and J. E. Taunton., 1985; Richards, Craig E., Parker J. Magin, and Robin Callister., 2009). Based on this study, a shoe which restricts excessive calcaneal plantar flexion may be more effective at influencing injury risk associated with structural arch differences. This shoe design, however, would be challenging to develop as some plantar flexion of the calcaneus during heel strike, as seen in the average foot, may be necessary. Therefore, the shoe would have to allow normal but prevent excessive plantar flexion of the calcaneus. This further highlights the importance of identifying the normal range of motion for calcaneal plantar flexion across a range of tasks.

Orthotics

Similar to athletic shoes, orthotics have been used to keep an individual's foot within the normal range of function and structure. Patients who have injuries typical of a flexible flatfoot and are diagnosed with flatfeet are typically prescribed orthotics to prevent the excessive deformation of the MLA (McKenzie, D. C., D. B. Clement, and J. E. Taunton., 1985; B. M. Nigg et al., 1999). The design of orthotics are similar to athletic shoes, in that they typically only provide support for the medial portion of the arch and rearfoot. Custom and mass-marketed orthotics could both benefit from preventing calcaneal plantar flexion to minimize movement of the MLA rather than a medial support, since calcaneal eversion was not found to correlate with either functional or structural foot arch type. To prevent calcaneal plantar flexion using an orthotic, the arch of the orthotic would need to be adjusted so it is closer to the rearfoot and stops excessive calcaneal plantar flexion. Different activities may require adjustments to orthotics to reflect diverse calcaneal tendon tension during the task and its effect on maximal calcaneal plantar flexion and functional arch movement.

Functional Arch Measurement

The methodology in this study provided a method for simulating the non-weight bearing position of the MLA, however it should be improved upon. This study found that the LAA measurement at weight bearing (structural arch type) was a better indicator of calcaneal plantar flexion during midstance than the change in LAA (functional arch type). This could indicate that the non-weight bearing position should be further perfected. Research into movement of the MLA during gait, as well as during running and other tasks, should be performed. The effect of changing calcaneal tendon tensions on maximum calcaneal plantar flexion, and therefore functional foot arch type, should be determined. This research is necessary to determine a better method for measuring functional foot arch type. This is important to allow for a gold-standard clinical foot arch type test to be identified. A better functional arch type measurement could allow for improved diagnosis and treatment of injuries related to foot arch dysfunction. Functional arch types may need to be measured based on the task being performed since based on calcaneal tendon tension the resulting functional arch type could be different for each task.

Participants

To provide a more robust analysis of the effect of calcaneal plantar flexion on structural and functional arch types as well as to better determine the range of calcaneal excursions during early and midstance, participants with all measured change in LAA should be analyzed. Since participants with feet with less than 5° of LAA change from non-weight bearing to weight bearing were excluded from this study, they still need to be measured to identify rotations occurring in their feet. More participants outside of the "normal" range, both rigid and flexible, should be studied to determine segment rotations in their feet during different tasks. This would provide a better picture of the full range of calcaneal excursions and structural and functional arch types. More participants within the "normal" range should also be included to determine the full range of calcaneal excursions possible.

Future Directions

Based on the results of this research, the next step would be to expand the range of participants measured to get a better description of possible calcaneal excursions and arch types. Including all arch types as well as analyzing more normal arch types would be important to more fully characterize the possible calcaneal plantar flexion excursions.

Different populations would also be important to look at to determine any systematic differences which occur. Key groups to look at would include high activity and foot stress groups, such as runners, cross country skiers, or other sports. This group could identify changes that may occur due to activity. Another important group to characterize would be people with foot injury or pain. Determining differences in this group compared to the average population could give more insight into the importance, or lack of importance, of calcaneal plantar flexion and its connection to injuries.

Moving forward, it is important to identify groups which could be affected by injuries or training, and to better characterize calcaneal segment rotation during stance for all groups.

Appendices

Appendix A: Data Processing Parameters

Forefoot: Proximal Lat = Base of 5^{th}, Med = Base of 1^{st}. Distal Lat = Head 5^{th}, Med = head 1st

Footflat: 1 frame after Distal End Velocity of forefoot =-0.02 on ascent

Calcaneal Rotation: Joint angle. Segment = Vertical Calcaneus. Reference = Lab. Cardan = ZYX

Forefoot Rotation: Joint Angle. Segment = Forefoot. Reference = Lab. Cardan = ZYX

Arch Angle.: Joint angle. Segment = R1Met-Nav. Reference = RNav-mal. Cardan = ZYX

Ankle Angle: Joint angle. Segment = Vertical Calcaneus. Reference = Shank. Cardan = ZYX

Shank Angle: Joint angle. Segment = Shank. Reference = Lab. Cardan = ZYX

Knee Angle: Joint angle. Segment = Shank. Reference = Thigh. Cardan = ZYX

Hip Angle: Joint angle. Segment = Thigh. Reference = Pelvis. Cardan = ZYX

Thigh Angle: Joint Angle. Segment = Thigh. Reference = lab. Cardan = ZYX

COP: COP path. Segment = Foot. Resolution Coordinate System = lab

Knee Moment: Joint Moment. Joint = Knee. RCS = Shank. Normalization off. Cardan Off

Hip Moment: Joint Moment. Joint = Hip. RCS = Thigh. Normalization off. Cardan Off

Ankle Moment: Joint Moment. Joint = Angle. RCS = Foot. Normalization off. Cardan Off

Knee Flexor 1: Between HS and FF

Knee Extensor: Between HS and FF

Knee Flexor 2: Between FF and OFF

Appendix B: Participant Data

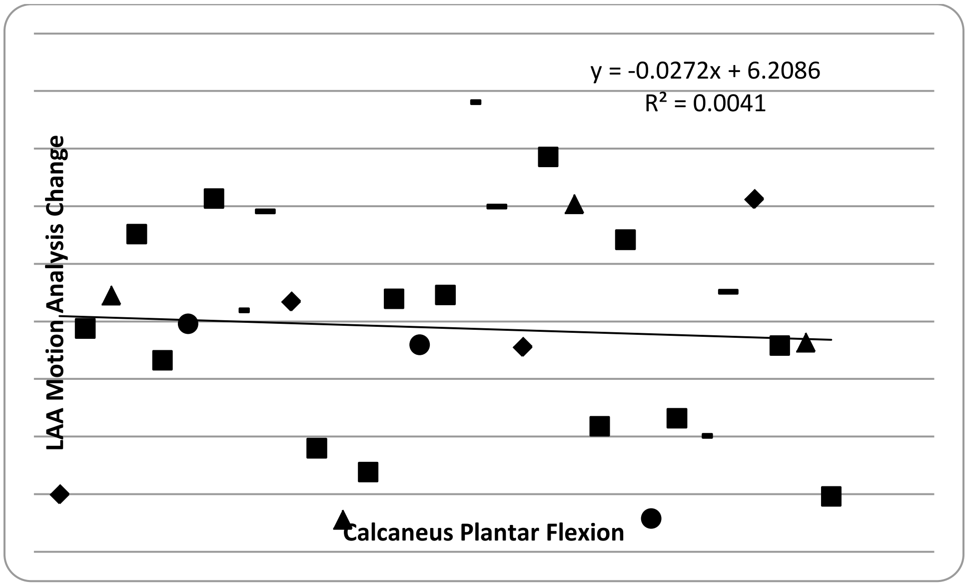
Subject	Side	Height	Weight	Ft_Lng	Day_Ex	Cal_Rot	FF_Rot	Calc_Fnt
F01	R	174.5	66.5	25.5	5	19.6	21.2	5.3
F02	R	176	66.6	25.2	4	18.3	19.4	8.4
F03	R	172.2	74.6	25	3	17.9	14.3	4.1
F04	R	167	63	25.2	6	20.6	17.9	9.9
F05	R	162.5	65.4	23.8	4	22.7	17.9	7.5
F06	R	173.5	65.5	24	7	27.6	17.7	4.5
F07	R	160	59	23	2.50	20.2	18.6	7.0
F08	R	159.5	57.6	23.2	4	24.6	21.7	6.4
F09	R	131.5	56.9	23	6	22.7	19.4	4.1
F10	R	158	62.5	22.2	3	26.8	19.5	6.9
F11	R	167.5	61.4	23	4	24.5	12.3	6.1
F12	R	171.5	64	22.3	4	18.8	15.9	6.7
F13	R	174	63.3	23.4	3	19.9	18.1	8.2
F14	R	159	57.9	21.3	0	20.4	20.1	10.8
F15	R	170	78.4	24.3	4	23.5	17.1	4.2
F16	R	170.5	85.2	23.7	5	24.5	15.3	7.5
M01	R	175.5	74.4	26	7	21.4	21.5	4.6
M02	R	177.5	74.4	25.5	6	23.0	22.2	1.8
M03	R	170	65.2	24.4	6	24.1	9.9	19.3
M04	R	179	83.5	25.4	6	28.4	19.6	0.7
M05	R	175.5	80.3	25.4	2	33.8	8.0	1.5
M06	R	187.5	92	27.9	7	19.2	18.3	6.5
M07	R	185	120.8	26.8	4	23.3	24.1	7.3
M08	R	185	67.3	26.1	7	13.7	13.4	3.3
M09	R	179.5	126.1	24.5	2	20.3	22.0	5.9
M10	R	175	84.2	25.5	6	17.2	18.2	7.6
M11	R	176.5	87.5	26	6	15.1	15.6	7.6
M12	R	171.5	74.4	26	6	21.7	18.6	5.8
M13	R	166.5	63.2	23.4	7	21.8	16.3	7.3
M14	R	173	70.4	26.4	7	25.7	14.0	-0.1
F01	L	174.5	66.5	25.8	5	18.3	21.7	6.4
F02	L	176	66.6	25.1	4	24.3	19.0	0.7
F03	L	172.2	74.6	24.2	3	12.3	15.1	-0.4
F04	L	167	63	25.4	6	22.6	19.2	2.9
F05	L	162.5	65.4	23.4	4	23.9	19.2	3.3
F06	L	173.5	65.5	24.1	7	16.2	18.8	3.9
F07	L	160	59	23	2.50	20.0	17.3	6.1
F08	L	159.5	57.6	23	4	20.6	18.3	0.3
F09	L	131.5	56.9	22.9	6	17.4	18.2	5.1
F10	L	158	62.5	22.3	3	19.2	22.3	4.6
F11	L	167.5	61.4	22.7	4	20.1	16.1	5.0
F12	L	171.5	64	22.3	4	17.1	14.8	6.1
F13	L	174	63.3	23.7	3	20.3	19.6	10.2
F14	L	159	57.9	21.5	0	18.4	14.2	9.0
F15	L	170	78.4	23.9	4	21.2	18.4	4.5
F16	L	170.5	85.2	23.5	5	17.2	20.2	5.2
M01	L	175.5	74.4	26.2	7	17.9	17.2	1.5
M02	L	177.5	74.4	25.4	6	20.8	18.1	3.4
M03	L	170	65.2	25.4	6	13.2	1.4	-0.8
M04	L	179	83.5	25.4	6	16.9	20.8	8.4
M05	L	175.5	80.3	25.3	2	30.6	9.0	2.2
M06	L	187.5	92	27.9	7	20.5	16.5	5.6
M07	L	185	120.8	26	4	11.8	20.3	4.7
M08	L	185	67.3	26.3	7	17.6	14.3	-3.0
M09	L	179.5	126.1	24.3	2	17.3	22.2	3.2
M10	L	175	84.2	25.5	6	18.2	17.0	5.0
M11	L	176.5	87.5	25.5	6	14.9	18.4	2.4
M12	L	171.5	74.4	26.1	6	16.5	19.8	5.4
M13	L	166.5	63.2	23.2	7	19.6	16.7	6.7
M14	L	173	70.4	26.2	7	26.4	19.3	-2.4
Right AVG	R	170.8	73.7	24.6	4.8	22.1	17.6	6.2
Right SD	R	10.6	16.6	1.5	1.8	4.1	3.7	3.5
Left AVG	L	170.8	73.7	24.5	4.8	19.1	17.4	3.8
Left SD	L	10.6	16.6	1.5	1.8	3.9	4.1	3.1

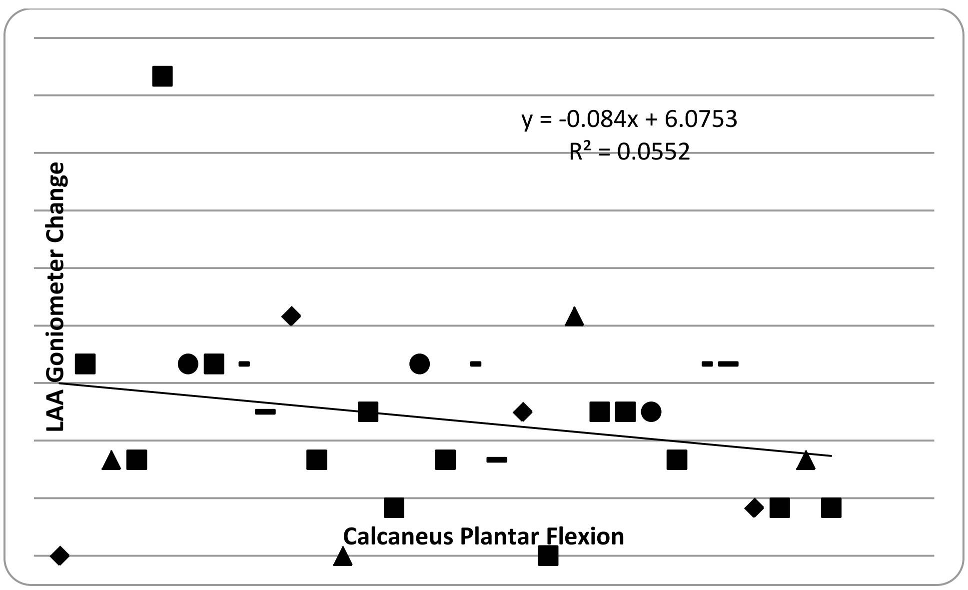
Subject	LAA MA Δ	LAA Gon Δ	LAA Gon @ WB	LAA MA @ WB	Calc Mx Rt	Arch Mx Rt	Arch Rot	Nav Drop
F01	-5.8	6.7	146.7	136.4	27.8	-1.4	-1.5	5.90E-03
F02	-6.9	3.3	155.0	153.3	28.9	9.1	5.7	5.16E-03
F03	-9.0	3.3	151.7	160.1	23.8	3.0	4.2	4.95E-03
F04	-4.6	16.7	123.3	128.2	30.8	7.4	2.6	4.49E-03
F05	-5.9	6.7	140.0	143.0	33.0	10.7	6.5	9.54E-03
F06	-10.3	6.7	150.0	143.9	35.6	11.3	11.1	5.39E-03
F07	-6.4	6.7	148.3	150.5	28.5	5.2	2.1	3.14E-03
F08	-9.8	5.0	135.0	129.7	32.7	4.8	2.9	3.72E-03
F09	-6.7	8.3	145.0	148.6	30.3	6.0	3.6	7.49E-03
F10	-1.6	3.3	150.0	146.6	42.5	15.3	7.0	-2.56E-03
F11	0.9	0.0	143.3	136.9	32.1	12.8	11.3	1.37E-03
F12	-0.8	5.0	145.0	142.6	26.4	7.6	4.3	-2.65E-04
F13	-6.8	1.7	151.7	156.6	24.8	1.7	3.4	-3.91E-04
F14	-5.2	6.7	145.0	147.8	31.5	6.5	2.4	5.22E-03
F15	-6.9	3.3	148.3	148.9	27.5	6.8	6.1	4.11E-03
F16	-13.6	6.7	151.7	148.2	30.4	11.6	11.0	4.92E-03
M01	-10.0	3.3	160.0	157.4	29.3	0.9	0.4	9.02E-03
M02	-5.1	5.0	138.3	138.4	31.0	5.3	1.0	2.26E-03
M03	-11.7	0.0	153.3	135.3	30.5	60.3	71.0	6.17E-03
M04	-10.1	8.3	151.7	156.4	18.7	13.7	11.2	5.24E-03
M05	-2.4	5.0	150.0	131.8	42.2	16.5	14.0	6.82E-04
M06	-8.8	5.0	148.3	152.1	28.1	1.9	1.4	8.52E-03
M07	0.8	5.0	141.7	140.0	29.9	2.3	1.0	2.88E-03
M08	-2.6	3.3	175.0	167.4	27.1	8.0	1.4	7.84E-03
M09	-2.0	6.7	146.7	143.1	26.2	5.0	1.4	-3.32E-03
M10	-7.0	6.7	165.0	162.8	22.0	4.6	1.9	1.09E-02
M11	-10.3	1.7	148.3	149.3	15.2	4.2	2.1	3.75E-03
M12	-5.2	1.7	151.7	148.7	30.0	6.6	4.6	3.12E-03
M13	-5.3	3.3	150.0	150.1	30.6	7.9	5.3	-4.39E-03
M14	0.1	1.7	135.0	124.8	33.6	13.2	11.4	-2.17E-03
F01	-6.9	1.7	153.3	146.4	28.4	-1.8	0.1	4.07E-03
F02	-6.3	5.0	151.7	154.8	36.7	-7.7	5.5	4.64E-03
F03	-2.0	5.0	158.3	156.4	17.4	-5.7	-1.8	3.60E-03
F04	-6.9	10.0	125.0	121.6	30.2	-1.4	4.2	-1.40E-03
F05	-2.3	-1.7	150.0	143.2	29.3	-0.7	6.2	4.72E-03
F06	-5.9	5.0	150.0	138.2	22.5	-2.6	-1.5	4.31E-03
F07	-8.2	5.0	150.0	150.1	25.3	-0.6	3.6	7.48E-03
F08	-7.6	6.7	146.7	132.5	26.7	-0.8	2.8	3.23E-03
F09	-6.9	5.0	150.0	152.5	23.7	0.2	0.9	5.12E-03
F10	-4.8	5.0	150.0	146.5	34.9	-9.6	-2.3	1.63E-03
F11	-2.3	1.7	141.7	139.6	25.6	-1.2	4.8	4.38E-03
F12	-3.6	0.0	150.0	148.2	22.1	0.6	3.3	-1.48E-04
F13	-5.0	5.0	153.3	154.5	24.4	1.4	3.3	2.27E-03
F14	-6.8	3.3	138.3	148.3	30.3	-2.9	5.4	5.66E-03
F15	0.0	3.3	146.7	148.4	27.6	-0.5	3.4	4.56E-04
F16	-1.2	1.7	155.0	151.4	23.3	-0.4	-1.6	1.55E-03
M01	-15.6	6.7	153.3	158.5	27.6	-4.2	-0.9	1.55E-02
M02	-3.4	1.7	145.0	146.9	28.3	-6.0	-3.4	-1.08E-03
M03	-9.6	3.3	145.0	137.8	36.2	-29.1	-6.9	3.83E-03
M04	-8.1	6.7	158.3	150.2	22.2	-0.8	0.4	7.22E-03
M05	-4.2	-1.7	151.7	136.2	40.9	-17.7	-10.3	3.53E-05
M06	-6.8	0.0	155.0	151.9	30.2	-5.0	-5.1	6.47E-03
M07	-3.9	1.7	151.7	151.2	18.0	2.3	6.1	6.66E-03
M08	-11.3	0.0	160.0	156.8	24.7	-1.8	-1.1	8.40E-03
M09	-9.9	1.7	156.7	160.6	22.9	0.0	2.0	5.94E-03
M10	-12.1	6.7	156.7	167.0	24.3	-4.3	-2.7	8.61E-03
M11	-13.3	6.7	151.7	147.3	17.5	2.5	1.6	5.58E-03
M12	-7.7	0.0	145.0	151.2	23.2	-0.4	1.1	2.73E-03
M13	-6.0	5.0	151.7	159.7	28.6	-8.6	-4.8	1.76E-03
M14	-2.8	5.0	130.0	125.0	35.2	-9.9	-7.9	-5.00E-03
Right AVG	-6	4.9	148.2	146.0	29.4	9.0	7.0	0.00
Right SD	3.8	3.2	9.3	10.4	5.6	10.7	12.7	0.00
Left AVG	-6.4	3.5	149.4	147.8	26.9	-3.9	0.1	0.00
Left SD	3.7	2.9	7.8	10.1	5.7	6.4	4.3	0.00

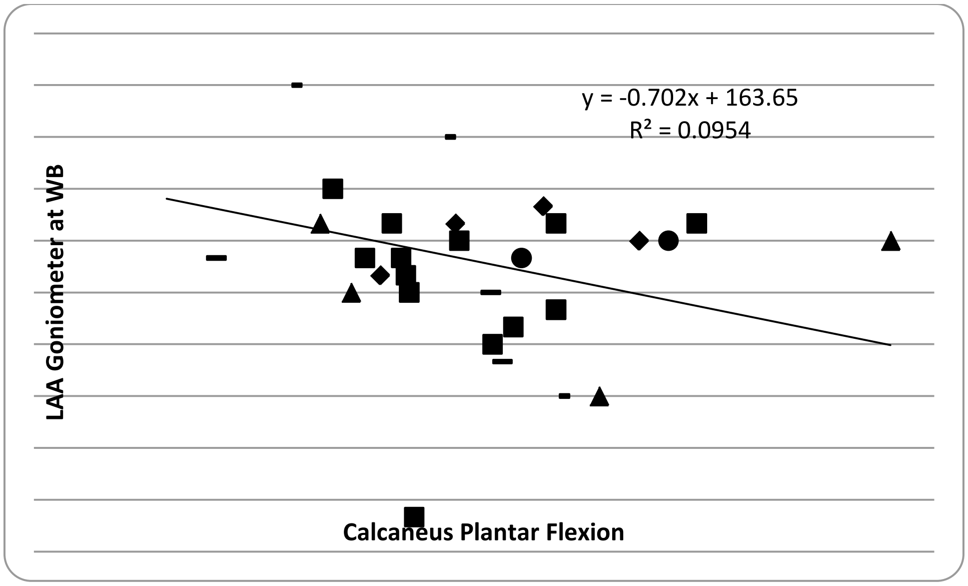
Subject	AVG Calc Rot	AVG FF Rot	AVG Calc Fnt	AVG LAA MA Δ	AVG LAA Gon Δ	AVG LAA MA @ WB	AVG LAA Gon @ WB	AVG Nav Drop
F01	19.0	21.5	5.9	-6.3	-4.2	141.4	150.0	4.98E-03
F02	21.3	19.2	4.6	-6.6	-4.2	154.0	153.3	4.90E-03
F03	15.1	14.7	1.9	-5.5	-4.2	158.3	155.0	4.27E-03
F04	21.6	18.5	6.4	-5.8	-13.3	124.9	124.2	1.54E-03
F05	23.3	18.5	5.4	-4.1	-2.5	143.1	145.0	7.13E-03
F06	21.9	18.2	4.2	-8.1	-5.8	141.0	150.0	4.85E-03
F07	20.1	18.0	6.5	-7.3	-5.8	150.3	149.2	5.31E-03
F08	22.6	20.0	3.3	-8.7	-5.8	131.1	140.8	3.48E-03
F09	20.1	18.8	4.6	-6.8	-6.7	150.5	147.5	6.31E-03
F10	23.0	20.9	5.7	-3.2	-4.2	146.6	150.0	-4.62E-04
F11	22.3	14.2	5.5	-0.7	-0.8	138.2	142.5	2.87E-03
F12	18.0	15.3	6.4	-2.2	-2.5	145.4	147.5	-2.06E-04
F13	20.1	18.9	9.2	-5.9	-3.3	155.6	152.5	9.38E-04
F14	19.4	17.1	9.9	-6.0	-5.0	148.0	141.7	5.44E-03
F15	22.4	17.8	4.4	-3.5	-3.3	148.7	147.5	2.28E-03
F16	20.8	17.7	6.3	-7.4	-4.2	149.8	153.3	3.24E-03
M01	19.7	19.3	3.0	-12.8	-5.0	157.9	156.7	1.23E-02
M02	21.9	20.1	2.6	-4.2	-3.3	142.6	141.7	5.91E-04
M03	18.7	5.6	9.3	-10.6	-1.7	136.6	149.2	5.00E-03
M04	22.7	20.2	4.6	-9.1	-7.5	153.3	155.0	6.23E-03
M05	32.2	8.5	1.9	-3.3	-1.7	134.0	150.8	3.59E-04
M06	19.8	17.4	6.0	-7.8	-2.5	152.0	151.7	7.50E-03
M07	17.5	22.2	6.0	-1.5	-3.3	145.6	146.7	4.77E-03
M08	15.7	13.8	0.2	-7.0	-1.7	162.1	167.5	8.12E-03
M09	18.8	22.1	4.5	-6.0	-4.2	151.9	151.7	1.31E-03
M10	17.7	17.6	6.3	-9.6	-6.7	164.9	160.8	9.76E-03
M11	15.0	17.0	5.0	-11.8	-4.2	148.3	150.0	4.66E-03
M12	19.1	19.2	5.6	-6.4	-0.8	149.9	148.3	2.92E-03
M13	20.7	16.5	7.0	-5.7	-4.2	154.9	150.8	-1.31E-03
M14	26.0	16.6	-1.2	-1.3	-3.3	124.9	132.5	-3.59E-03
Average	20.6	17.5	5.0	-6.2	-4.2	146.9	148.8	0.0
SD	3.3	3.6	2.4	3.0	2.4	9.8	7.9	0.0

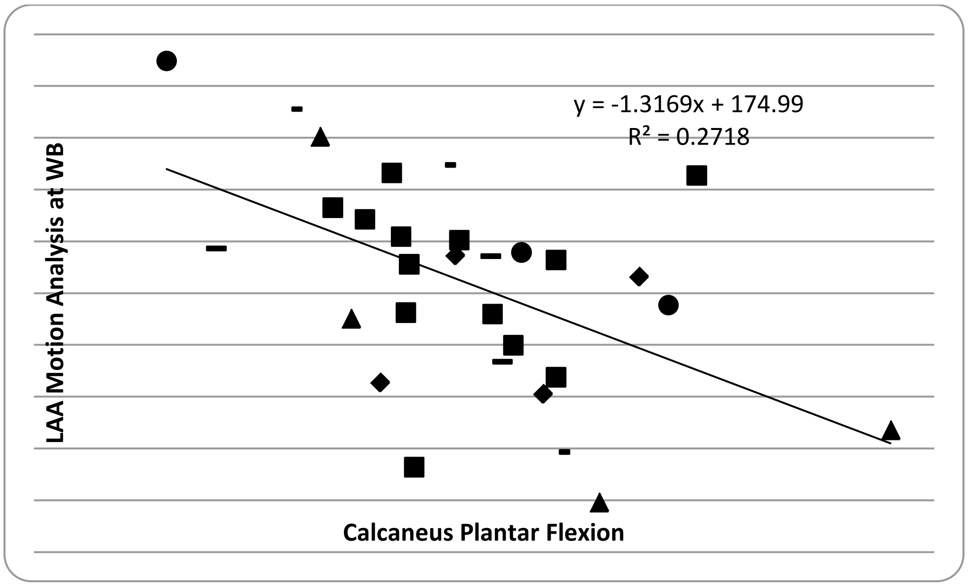
Appendix C: Correlation Results

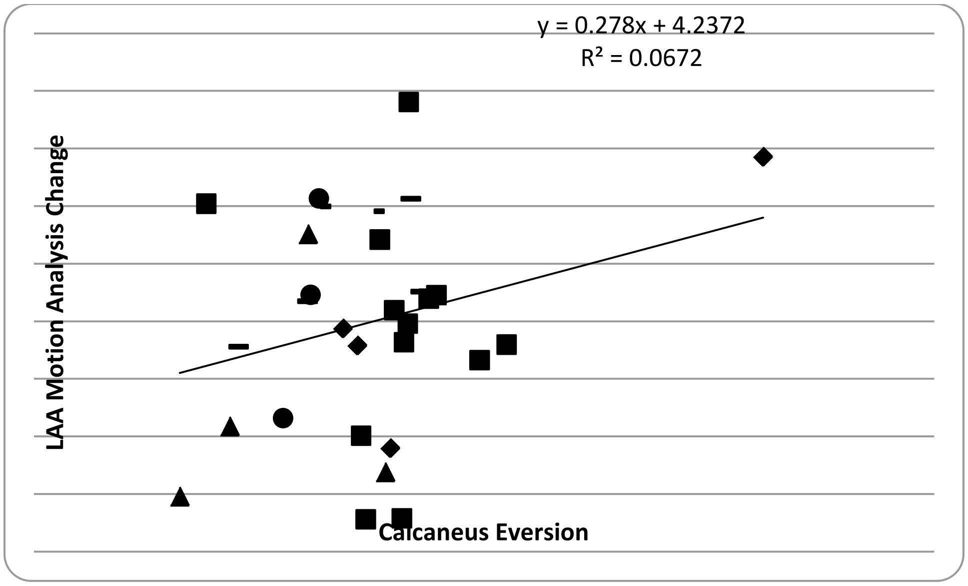
Right Correlation Graphs

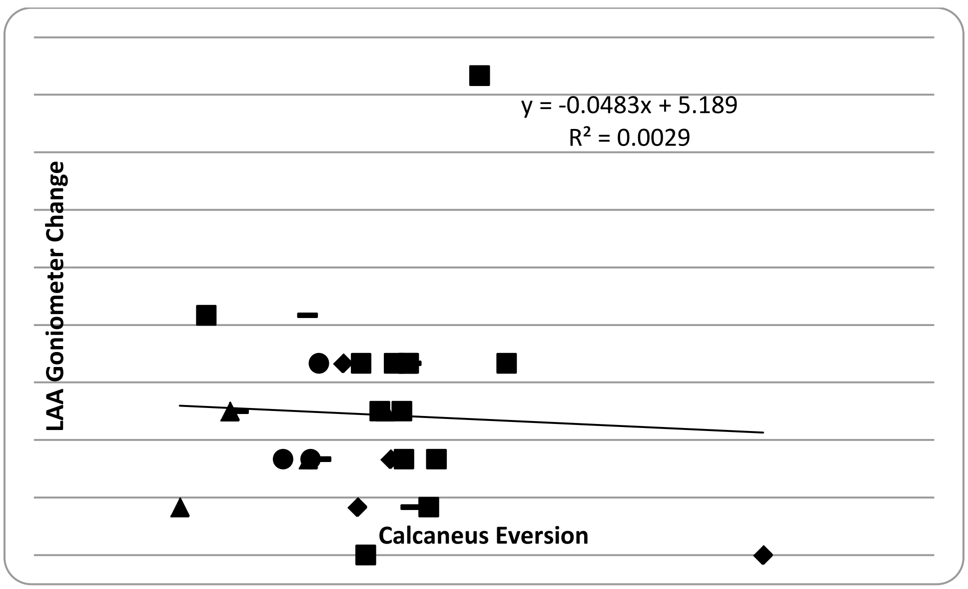


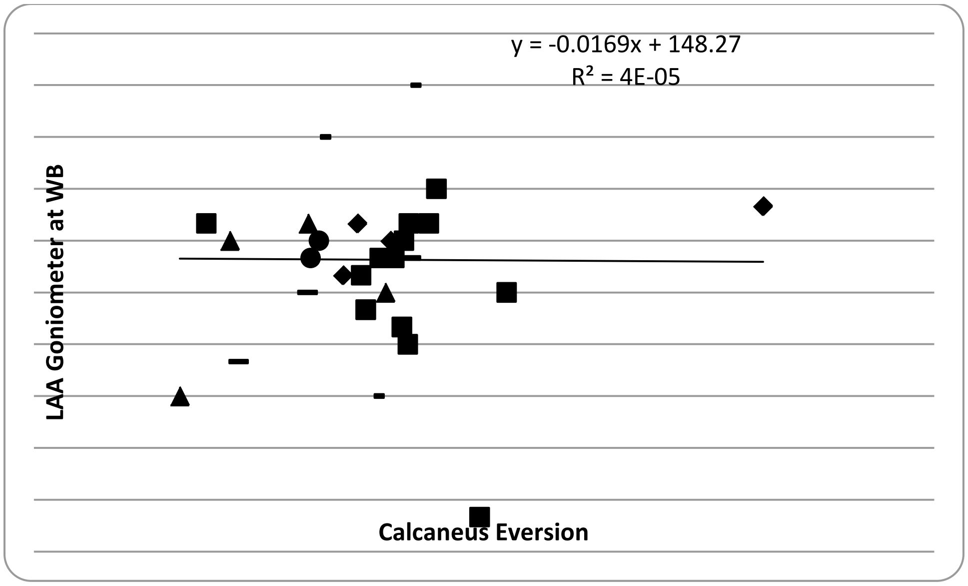


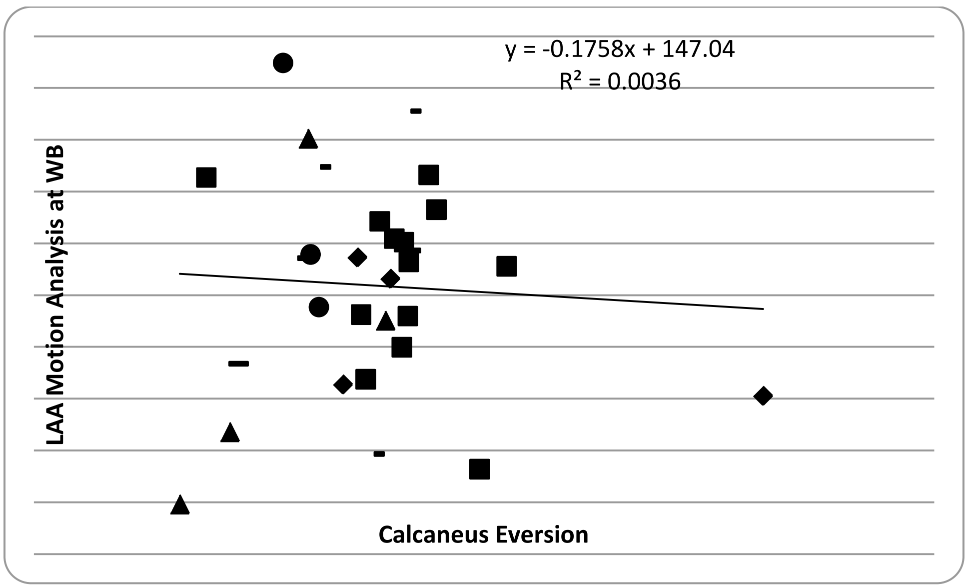

y = -0.702x + 163.65
R² = 0.0954
LAA Goniometer at WB
Calcaneus Plantar Flexion


y = -1.3169x + 174.99
R² = 0.2718
LAA Motion Analysis at WB
Calcaneus Plantar Flexion


y = 0.278x + 4.2372
R² = 0.0672
LAA Motion Analysis Change
Calcaneus Eversion


y = -0.0483x + 5.189
R² = 0.0029
LAA Goniometer Change
Calcaneus Eversion


y = -0.0169x + 148.27
R² = 4E-05
LAA Goniometer at WB
Calcaneus Eversion


y = -0.1758x + 147.04
R² = 0.0036
LAA Motion Analysis at WB
Calcaneus Eversion

Right Correlation Data

Correlations

		Gender	Cal_Sag	FF_Fmt	Calc_Fmt	LAA
Gender	Pearson Correlation	1	.001	-.088	-.153	.071
	Sig. (2-tailed)		.997	.643	.421	.709
	N	30	30	30	30	30
Cal_Sag	Pearson Correlation	.001	1	-.194	-.247	.061
	Sig. (2-tailed)	.997		.304	.188	.749
	N	30	30	30	30	30
FF_Fmt	Pearson Correlation	-.088	-.194	1	-.102	-.011
	Sig. (2-tailed)	.643	.304		.593	.953
	N	30	30	30	30	30
Calc_Fmt	Pearson Correlation	-.153	-.247	-.102	1	-.259
	Sig. (2-tailed)	.421	.188	.593		.167
	N	30	30	30	30	30
LAA	Pearson Correlation	.071	.061	-.011	-.259	1
	Sig. (2-tailed)	.709	.749	.953	.167	
	N	30	30	30	30	30
Scrn_Chng	Pearson Correlation	-.251	.038	.341	-.054	-.072
	Sig. (2-tailed)	.180	.843	.065	.778	.706
	N	30	30	30	30	30
Scrn_WB	Pearson Correlation	.297	-.309	-.210	-.006	-.222
	Sig. (2-tailed)	.112	.097	.266	.973	.238
	N	30	30	30	30	30
LAA_WB	Pearson Correlation	.093	-.521**	.104	-.060	-.307
	Sig. (2-tailed)	.625	.003	.585	.752	.099
	N	30	30	30	30	30
Calc_MxSag	Pearson Correlation	-.206	.643**	-.160	-.035	.339
	Sig. (2-tailed)	.275	.000	.399	.855	.067
	N	30	30	30	30	30
Arch_MxRt	Pearson Correlation	.159	.356	-.569**	.547**	-.169
	Sig. (2-tailed)	.400	.054	.001	.002	.373
	N	30	30	30	30	30
Arch_Rot	Pearson Correlation	.158	.322	-.557**	.576**	-.259
	Sig. (2-tailed)	.403	.083	.001	.001	.167
	N	30	30	30	30	30
Nav_Chng	Pearson Correlation	-.037	-.284	.081	.141	-.515**
	Sig. (2-tailed)	.848	.129	.669	.457	.004
	N	30	30	30	30	30

Page 1

Correlations

		Scrn_Chng	Scrn_WB	LAA_WB	Calc_MxSag	Arch_MxRt
Gender	Pearson Correlation	-.251	.297	.093	-.206	.159
	Sig. (2-tailed)	.180	.112	.625	.275	.400
	N	30	30	30	30	30
Cal_Sag	Pearson Correlation	.038	-.309	-.521**	.643**	.356
	Sig. (2-tailed)	.843	.097	.003	.000	.054
	N	30	30	30	30	30
FF_Fmt	Pearson Correlation	.341	-.210	.104	-.160	-.569**
	Sig. (2-tailed)	.065	.266	.585	.399	.001
	N	30	30	30	30	30
Calc_Fmt	Pearson Correlation	-.054	-.006	-.060	-.035	.547**
	Sig. (2-tailed)	.778	.973	.752	.855	.002
	N	30	30	30	30	30
LAA	Pearson Correlation	-.072	-.222	-.307	.339	-.169
	Sig. (2-tailed)	.706	.238	.099	.067	.373
	N	30	30	30	30	30
Scrn_Chng	Pearson Correlation	1	-.401*	-.147	.011	-.270
	Sig. (2-tailed)		.028	.438	.956	.150
	N	30	30	30	30	30
Scrn_WB	Pearson Correlation	-.401*	1	.801**	-.257	.068
	Sig. (2-tailed)	.028		.000	.170	.720
	N	30	30	30	30	30
LAA_WB	Pearson Correlation	-.147	.801**	1	-.510**	-.282
	Sig. (2-tailed)	.438	.000		.004	.131
	N	30	30	30	30	30
Calc_MxSag	Pearson Correlation	.011	-.257	-.510**	1	.244
	Sig. (2-tailed)	.956	.170	.004		.194
	N	30	30	30	30	30
Arch_MxRt	Pearson Correlation	-.270	.068	-.282	.244	1
	Sig. (2-tailed)	.150	.720	.131	.194	
	N	30	30	30	30	30
Arch_Rot	Pearson Correlation	-.317	.075	-.266	.161	.978**
	Sig. (2-tailed)	.088	.694	.156	.396	.000
	N	30	30	30	30	30
Nav_Chng	Pearson Correlation	.237	.318	.372*	-.268	-.016
	Sig. (2-tailed)	.207	.087	.043	.153	.934
	N	30	30	30	30	30

Page 2

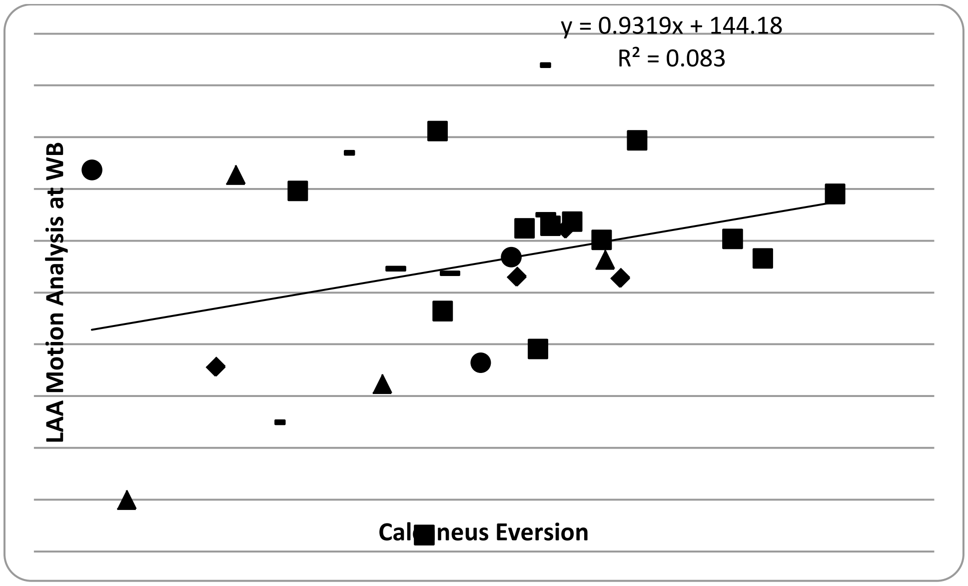
Correlations

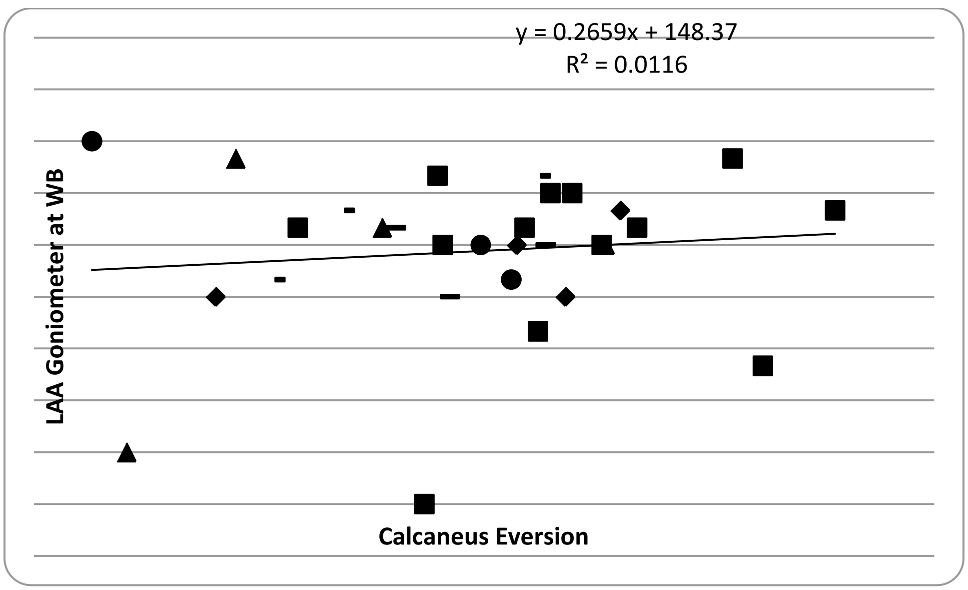
		Arch_Rot	Nav_Chng
Gender	Pearson Correlation	.158	-.037
	Sig. (2-tailed)	.403	.848
	N	30	30
Cal_Sag	Pearson Correlation	.322	-.284
	Sig. (2-tailed)	.083	.129
	N	30	30
FF_Fmt	Pearson Correlation	-.557**	.081
	Sig. (2-tailed)	.001	.669
	N	30	30
Calc_Fmt	Pearson Correlation	.576**	.141
	Sig. (2-tailed)	.001	.457
	N	30	30
LAA	Pearson Correlation	-.259	-.515**
	Sig. (2-tailed)	.167	.004
	N	30	30
Scrn_Chng	Pearson Correlation	-.317	.237
	Sig. (2-tailed)	.088	.207
	N	30	30
Scrn_WB	Pearson Correlation	.075	.318
	Sig. (2-tailed)	.694	.087
	N	30	30
LAA_WB	Pearson Correlation	-.266	.372*
	Sig. (2-tailed)	.156	.043
	N	30	30
Calc_MxSag	Pearson Correlation	.161	-.268
	Sig. (2-tailed)	.396	.153
	N	30	30
Arch_MxRt	Pearson Correlation	.978**	-.016
	Sig. (2-tailed)	.000	.934
	N	30	30
Arch_Rot	Pearson Correlation	1	.029
	Sig. (2-tailed)		.879
	N	30	30
Nav_Chng	Pearson Correlation	.029	1
	Sig. (2-tailed)	.879	
	N	30	30

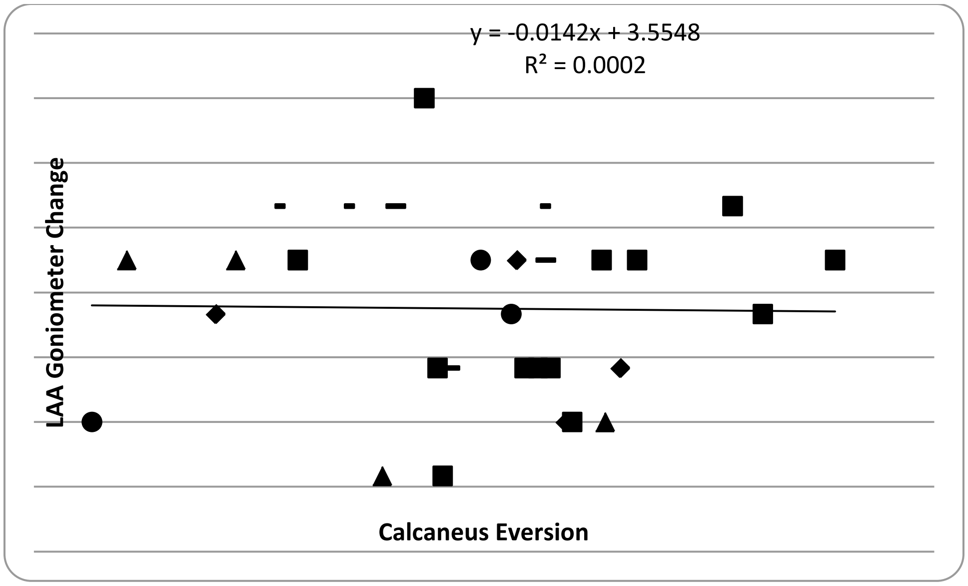
**. Correlation is significant at the 0.01 level (2-tailed).

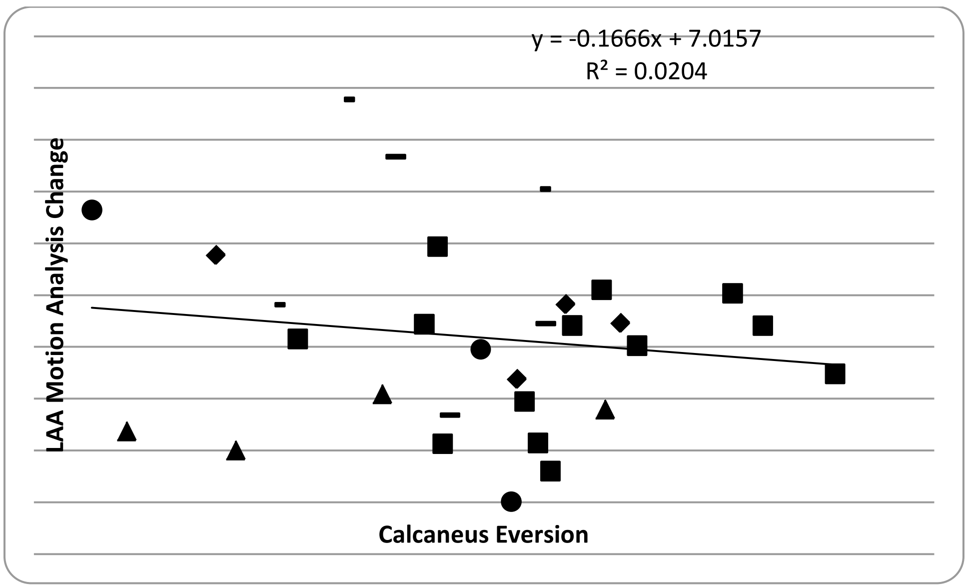
*. Correlation is significant at the 0.05 level (2-tailed).

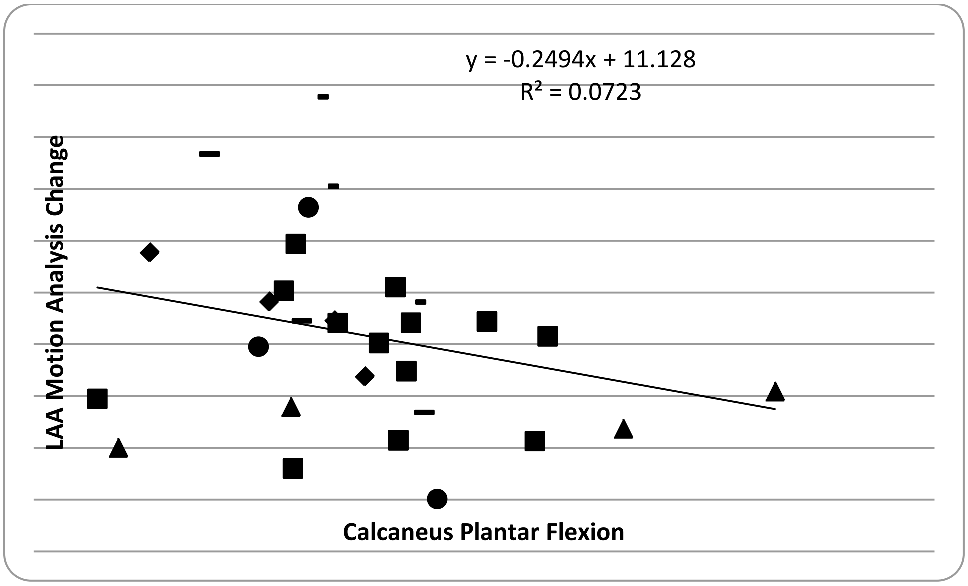
Left Correlation Graphs

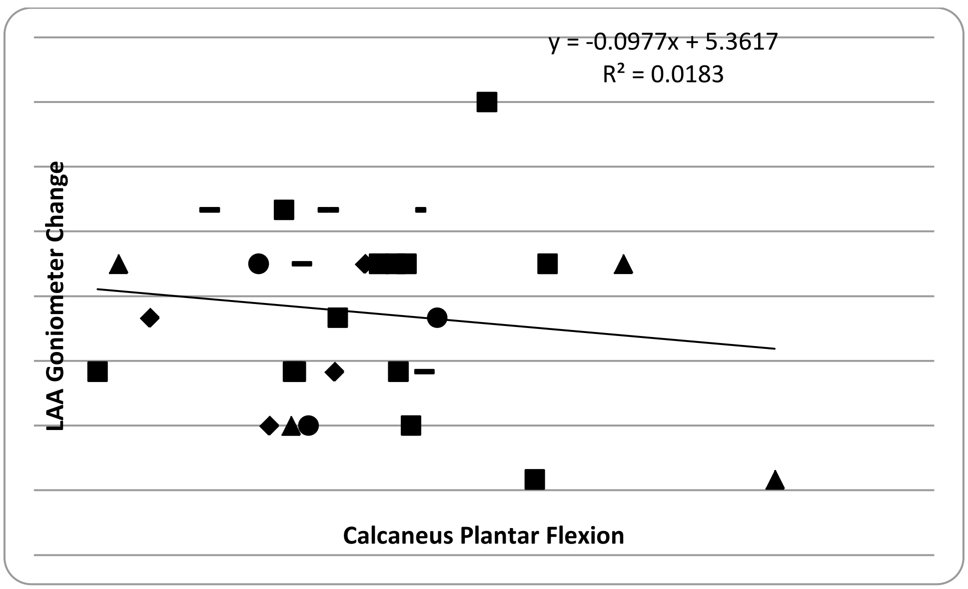


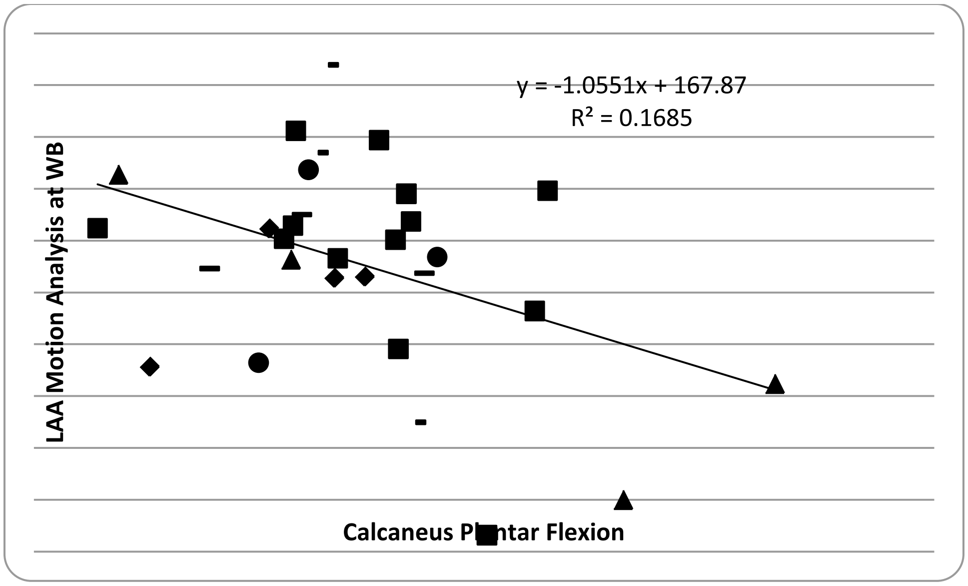


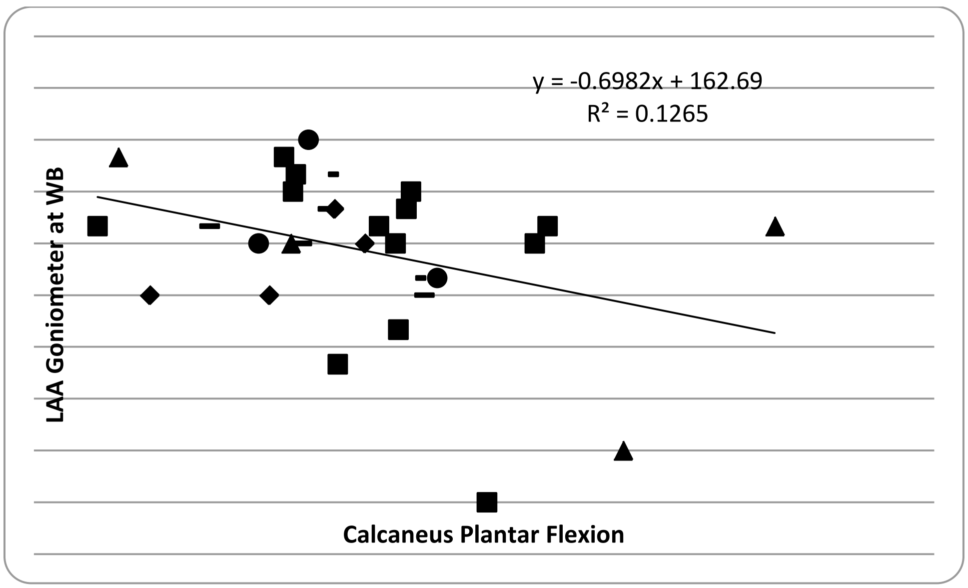

y = -0.0142x + 3.5548
R² = 0.0002
LAA Goniometer Change
Calcaneus Eversion


y = -0.1666x + 7.0157
R² = 0.0204
LAA Motion Analysis Change
Calcaneus Eversion


y = -0.2494x + 11.128
R^2 = 0.0723
LAA Motion Analysis Change
Calcaneus Plantar Flexion


y = -0.0977x + 5.3617
R^2 = 0.0183
LAA Goniometer Change
Calcaneus Plantar Flexion


y = -1.0551x + 167.87
R² = 0.1685
LAA Motion Analysis at WB
Calcaneus Plantar Flexion


y = -0.6982x + 162.69
R² = 0.1265
LAA Goniometer at WB
Calcaneus Plantar Flexion

Left Correlation Data

Correlations

		Gender	Cal_Sag	FF_Fmt	Calc_Fmt	LAA
Gender	Pearson Correlation	1	-.079	-.220	-.246	-.470**
	Sig. (2-tailed)		.680	.242	.191	.009
	N	30	30	30	30	30
Cal_Sag	Pearson Correlation	-.079	1	.014	-.101	.269
	Sig. (2-tailed)	.680		.944	.595	.151
	N	30	30	30	30	30
FF_Fmt	Pearson Correlation	-.220	.014	1	.323	.113
	Sig. (2-tailed)	.242	.944		.082	.552
	N	30	30	30	30	30
Calc_Fmt	Pearson Correlation	-.246	-.101	.323	1	.143
	Sig. (2-tailed)	.191	.595	.082		.452
	N	30	30	30	30	30
LAA	Pearson Correlation	-.470**	.269	.113	.143	1
	Sig. (2-tailed)	.009	.151	.552	.452	
	N	30	30	30	30	30
Scrn_Chng	Pearson Correlation	-.135	-.135	.198	-.016	-.353
	Sig. (2-tailed)	.476	.476	.293	.934	.056
	N	30	30	30	30	30
Scrn_WB	Pearson Correlation	.177	-.356	.063	.108	-.236
	Sig. (2-tailed)	.349	.054	.739	.571	.209
	N	30	30	30	30	30
LAA_WB	Pearson Correlation	.211	-.410*	.155	.288	-.309
	Sig. (2-tailed)	.262	.024	.415	.123	.097
	N	30	30	30	30	30
Calc_MxSag	Pearson Correlation	.030	.723**	-.372*	-.239	.113
	Sig. (2-tailed)	.873	.000	.043	.204	.552
	N	30	30	30	30	30
Arch_MxRt	Pearson Correlation	-.300	-.198	.749**	.408*	.021
	Sig. (2-tailed)	.107	.294	.000	.025	.911
	N	30	30	30	30	30
Arch_Rot	Pearson Correlation	-.537**	-.201	.433*	.333	.066
	Sig. (2-tailed)	.002	.287	.017	.072	.728
	N	30	30	30	30	30
Nav_Chng	Pearson Correlation	.204	-.416*	-.005	.059	-.692**
	Sig. (2-tailed)	.279	.022	.980	.755	.000
	N	30	30	30	30	30

Correlations

		Scrn_Chng	Scrn_WB	LAA_WB	Calc_MxSag	Arch_MxRt
Gender	Pearson Correlation	-.135	.177	.211	.030	-.300
	Sig. (2-tailed)	.476	.349	.262	.873	.107
	N	30	30	30	30	30
Cal_Sag	Pearson Correlation	-.135	-.356	-.410*	.723**	-.198
	Sig. (2-tailed)	.476	.054	.024	.000	.294
	N	30	30	30	30	30
FF_Fmt	Pearson Correlation	.198	.063	.155	-.372*	.749**
	Sig. (2-tailed)	.293	.739	.415	.043	.000
	N	30	30	30	30	30
Calc_Fmt	Pearson Correlation	-.016	.108	.288	-.239	.408*
	Sig. (2-tailed)	.934	.571	.123	.204	.025
	N	30	30	30	30	30
LAA	Pearson Correlation	-.353	-.236	-.309	.113	.021
	Sig. (2-tailed)	.056	.209	.097	.552	.911
	N	30	30	30	30	30
Scrn_Chng	Pearson Correlation	1	-.256	-.117	-.113	.073
	Sig. (2-tailed)		.173	.538	.551	.700
	N	30	30	30	30	30
Scrn_WB	Pearson Correlation	-.256	1	.774**	-.379*	.135
	Sig. (2-tailed)	.173		.000	.039	.477
	N	30	30	30	30	30
LAA_WB	Pearson Correlation	-.117	.774**	1	-.410*	.244
	Sig. (2-tailed)	.538	.000		.024	.193
	N	30	30	30	30	30
Calc_MxSag	Pearson Correlation	-.113	-.379*	-.410*	1	-.720**
	Sig. (2-tailed)	.551	.039	.024		.000
	N	30	30	30	30	30
Arch_MxRt	Pearson Correlation	.073	.135	.244	-.720**	1
	Sig. (2-tailed)	.700	.477	.193	.000	
	N	30	30	30	30	30
Arch_Rot	Pearson Correlation	.100	-.080	.101	-.423*	.701**
	Sig. (2-tailed)	.600	.675	.597	.020	.000
	N	30	30	30	30	30
Nav_Chng	Pearson Correlation	.095	.559**	.592**	-.322	.201
	Sig. (2-tailed)	.617	.001	.001	.083	.286
	N	30	30	30	30	30

Page 2

Correlations

		Arch_Rot	Nav_Chng
Gender	Pearson Correlation	-.537**	.204
	Sig. (2-tailed)	.002	.279
	N	30	30
Cal_Sag	Pearson Correlation	-.201	-.416*
	Sig. (2-tailed)	.287	.022
	N	30	30
FF_Fmt	Pearson Correlation	.433*	-.005
	Sig. (2-tailed)	.017	.980
	N	30	30
Calc_Fmt	Pearson Correlation	.333	.059
	Sig. (2-tailed)	.072	.755
	N	30	30
LAA	Pearson Correlation	.066	-.692**
	Sig. (2-tailed)	.728	.000
	N	30	30
Scrn_Chng	Pearson Correlation	.100	.095
	Sig. (2-tailed)	.600	.617
	N	30	30
Scrn_WB	Pearson Correlation	-.080	.559**
	Sig. (2-tailed)	.675	.001
	N	30	30
LAA_WB	Pearson Correlation	.101	.592**
	Sig. (2-tailed)	.597	.001
	N	30	30
Calc_MxSag	Pearson Correlation	-.423*	-.322
	Sig. (2-tailed)	.020	.083
	N	30	30
Arch_MxRt	Pearson Correlation	.701**	.201
	Sig. (2-tailed)	.000	.286
	N	30	30
Arch_Rot	Pearson Correlation	1	.230
	Sig. (2-tailed)		.221
	N	30	30
Nav_Chng	Pearson Correlation	.230	1
	Sig. (2-tailed)	.221	
	N	30	30

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Page 3

Bibliography

Arangio, G. A., Chen, C., & Salathé, E. P. (1998). Effect of varying arch height with and without the plantar fascia on the mechanical properties of the foot.
. *Foot & Ankle International, 19*(10), 705-709.

Bates, B. T., Osternig, L. R., Mason, B., & James, L. S. (1979). Foot orthotic devices to modify selected aspects of lower extremity mechanics.
. *The American Journal of Sports Medicine, 7*(6), 338-342.

Bruening, D. A., Cooney, K. M., & Buczek, F. L. (2012). Analysis of a kinetic multi-segment foot model. part I: Model repeatability and kinematic validity. *Gait & Posture, 35*(4), 529-534.

Bryanton, M. A., Kennedy, M. D., Carey, J. P., & Chiu, L. Z. (2012). Effect of squat depth and barbell load on relative muscular effort in squatting.
. *The Journal of Strength & Conditioning Research, 26*(10), 2820-2828.

Burns, J., Keenan, A., & Redmond, A. (2005). Foot type and overuse injury in triathletes. *Journal of the American Podiatric Medical Association, 95*(3), 235-241.

Butler, R. J., Davis, I. S., & Hamill, J. (2006). Interaction of arch type and footwear on running mechanics
. *The American Journal of Sports Medicine, 34*(12), 1998-2005.

Caravaggi, P., Pataky, T., Goulermas, J. Y., Savage, R., & Crompton, R. (2009). A dynamic model of the windlass mechanism of the foot: Evidence for early stance phase preloading of the plantar aponeurosis.
. *The Journal of Experimental Biology, 212*(15), 2491-2499.

Cavanagh, P. R., & Rodgers, M. M. (1987). The arch index: A useful measure from footprints. *Journal of Biomechanics, 20*(5), 547-551.

Cavanagh, P. R., Morag, E., Boulton, A. J. M., Young, M. J., Deffner, K. T., & Pammer, S. E. (1997). The relationship of static foot structure to dynamic foot function. *Journal of Biomechanics, 30*(3), 243-250. doi:10.1016/S0021-9290(96)00136-4

Cheng, H. K., Lin, C., Wang, H., & Chou, S. (2008). Finite element analysis of plantar fascia under stretch—The relative contribution of windlass mechanism and achilles tendon force. *Journal of Biomechanics, 41*(9), 1937-1944. doi:10.1016/j.jbiomech.2008.03.028

Chizewski, M. G., & Chiu, L. Z. (2012). Contribution of calcaneal and leg segment rotations to ankle joint dorsiflexion in a weight-bearing task. *Gait & Posture, 36*(1), 85-89. doi:10.1016/j.gaitpost.2012.01.007; 10.1016/j.gaitpost.2012.01.007

Chu, I., Myerson, M. S., Nyska, M., & Parks, B. G. (2001). Experimental flatfoot model: The contribution of dynamic loading. *Foot & Ankle International, 22*(3), 220-225.

Czerniecki, J. M. (1988). Foot and ankle biomechanics in walking and running: A review. *American Journal of Physical Medicine & Rehabilitation, 67*(6), 246-252.

Fascione, J. M., Crews, R. T., & Wrobel, J. S. (2012). Dynamic footprint measurement collection technique and intrarater reliability ink mat, paper pedography, and electronic pedography. *Journal of the American Podiatric Medical Association, 102*(2), 130-138.

Genova, J. M., & Gross, M. T. (2000). Effect of foot orthotics on calcaneal eversion during standing and treadmill walking for subjects with abnormal pronation.*
*. *The Journal of Orthopaedic and Sports Physical Therapy, 30*(11), 664-675.

Giddings, V. L., Beaupre, G. S., Whalen, R. T., & Carter, D. R. (2000). Calcaneal loading during walking and running. *Medicine and Science in Sports and Exercise, 32*(3), 627-634.

Goto, A., Moritomo, H., Itohara, T., Watanabe, T., & Sugamoto, K. (2009). Three-dimensional in vivo kinematics of the subtalar joint during dorsi-plantarflexion and inversion–eversion. *Foot & Ankle International, 30*(5), 432-438.

Gould, N. (1983). Evaluation of hyperpronation and pes planus in adults. *Clinical Orthopaedics and Related Research, 181*, 37-45.

Gray, H., Lewis, W. H., & Uahlthsc. (1918). *Anatomy of the human body* (20th / ed.). Philadelphia: Lea & Febiger.

Hamel, A. J., Sharkey, N. A., Buczek, F. L., & Michelson, J. (2004). Relative motions of the tibia, talus, and calcaneus during the stance phase of gait: A cadaver study. *Gait & Posture, 20*(2), 147-153.

Harris, R. I., & Beath, T. (1948). Hypermobile flat-foot with short tendo achillis.*
*. *The Journal of Bone & Joint Surgery, 30*(1), 115-150.

Harris, R. I., & Beath, T. (1948). Hypermobile flat-foot with short tendo achillis. *The Journal of Bone & Joint Surgery, 30*(1), 116-150.

Harris, E. J., Vanore, J. V., Thomas, J. L., Kravitz, S. R., Mendelson, S. A., Mendicino, R. W., . . . Gassen, S. C. (2004). Diagnosis and treatment of pediatric flatfoot. *The Journal of Foot and Ankle Surgery, 43*(6), 341-373. doi:10.1053/j.jfas.2004.09.013

Harris, E. J. (2010). The natural history and pathophysiology of flexible flatfoot. *Clinics in Podiatric Medicine and Surgery, 27*(1), 1-23. doi:10.1016/j.cpm.2009.09.002

Hicks, J. (1954). The mechanics of the foot: II. the plantar aponeurosis and the arch. *Journal of Anatomy, 88*(Pt 1), 25.

Huang, C., Kitaoka, H. B., An, K., & Chao, E. Y. (1993). Biomechanical evaluation of longitudinal arch stability. *Foot & Ankle International, 14*(6), 353-357.

Hunt, A. E., & Smith, R. M. (2004). Mechanics and control of the flat versus normal foot during the stance phase of walking.*
. Clinical Biomechanics, 19*(4), 391-397.

Imai, K., Tokunaga, D., Takatori, R., Ikoma, K., Maki, M., Ohkawa, H., . . . Kubo, T. (2009). In vivo three-dimensional analysis of hindfoot kinematics. *Foot & Ankle International, 30*(11), 1094-1100.

Iwanuma, S., Akagi, R., Hashizume, S., Kanehisa, H., Yanai, T., & Kawakami, Y. (2011). Triceps surae muscle-tendon unit length changes as a function of ankle joint angles and contraction levels: The effect of foot arch deformation. *Journal of Biomechanics, 44*(14), 2579-2583. doi:10.1016/j.jbiomech.2011.07.003; 10.1016/j.jbiomech.2011.07.003

Johanson, M. A., Donatelli, R., Wooden, M. J., Andrew, P. D., & Cummings, G. S. (1994). Effects of three different posting methods on controlling abnormal subtalar pronation.*
. Physical Therapy, 74*(2), 149-158.

Jonson, S., & Gross, M. (1997). Intraexaminer reliability, interexaminer reliability, and mean values for nine lower extremity skeletal measures in healthy naval midshipmen. *The Journal of Orthopaedic and Sports Physical Therapy, 25*(4), 253.

Kadaba, M., Ramakrishnan, H., Wootten, M., Gainey, J., Gorton, G., & Cochran, G. (1989). Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of Orthopaedic Research, 7*(6), 849-860.

Kappel-Bargas, A., Woolf, R. D., Cornwall, M. W., & McPoil, T. G. (1998). The windlass mechanism during normal walking and passive first metatarsalphalangeal joint extension. *Clinical Biomechanics, 13*(3), 190-194. doi:10.1016/S0268-0033(97)00038-7

Kaufman, K. R., Brodine, S. K., Shaffer, R. A., Johnson, C. W., & Cullison, T. R. (1999). The effect of foot structure and range of motion on musculoskeletal overuse injuries. *The American Journal of Sports Medicine, 27*(5), 585-593.

Kepple, T., Stanhope, S., Lohmann, K., & Roman, N. (1990). A video-based technique for measuring ankle—subtalar motion during stance. *Journal of Biomedical Engineering, 12*(4), 273-280.

Laquinto, J. M., & Wayne, J. S. (2010). Computational model of the lower leg and foot/ankle complex: Application to arch stability.*
*. *Journal of Biomechanical Engineering, 132*(2)

Leardini, A., Benedetti, M. G., Berti, L., Bettinelli, D., Nativo, R., & Giannini, S. (2007). Rear-foot, mid-foot and fore-foot motion during the stance phase of gait. *Gait & Posture, 25*(3), 453-462. doi:10.1016/j.gaitpost.2006.05.017

Leardini, A., Benedetti, M. G., Catani, F., Simoncini, L., & Giannini, S. (1999). An anatomically based protocol for the description of foot segment kinematics during gait. *Clinical Biomechanics, 14*(8), 528-536. doi:10.1016/S0268-0033(99)00008-X

Lersch, C., Grötsch, A., Segesser, B., Koebke, J., Brüggemann, G., & Potthast, W. (2012). Influence of calcaneus angle and muscle forces on strain distribution in the human achilles tendon. *Clinical Biomechanics,*

Lundberg, A., Svensson, O. K., Bylund, C., Goldie, I., & Selvik, G. (1989). Kinematics of the ankle/foot complex—part 2: Pronation and supination. *Foot & Ankle International, 9*(5), 248-253.

Lundberg, A. (1989). Kinematics of the ankle and foot: In vivo roentgen stereophotogrammetry. *Acta Orthopaedica, 60*(S233), 1-26.

Lundgren, P., Nester, C., Liu, A., Arndt, A., Jones, R., Stacoff, A., ... & Lundberg, A. (2008). Invasive in vivo measurement of rear-, mid-and forefoot motion during walking.*
*. *Gait & Posture, 28*(1), 93-100.

McKenzie, D. C., D. B. Clement, and J. E. Taunton. (1985). Running shoes, orthotics, and injuries. *Sports Medicine, 2*(5), 334-347.

McPoil, T. G., & Cornwall, M. W. (2005). Use of the longitudinal arch angle to predict dynamic foot posture in walking. *Journal of the American Podiatric Medical Association, 95*(2), 114-120.

Meehan, R. E., & Brage, M. (2003). Adult acquired flat foot deformity: Clinical and radiographic examination.
. *Foot and Ankle Clinics of North America, 8*(3), 431-452.

Moolyk, A. N., Carey, J. P., & Chiu, L. Z. (2013). Characteristics of lower extremity work during the impact phase of jumping and weightlifting
. *Journal of Strength and Conditioning Research/National Strength & Conditioning Association,*

Moseley, L., Smith, R., Hunt, A., & Gant, R. (1996). Three-dimensional kinematics of the rearfoot during the stance phase of walking in normal young adult males. *Clinical Biomechanics, 11*(1), 39-45. doi:10.1016/0268-0033(95)00036-4

Nakamura, H., & Kakurai, S. (2003). Relationship between the medial longitudinal arch movement and the pattern of rearfoot motion during the stance phase of walking. *Journal of Physical Therapy Science, 15*(1), 13-18.

Neptune, R. R., Kautz, S. A., & Zajac, F. E. (2001). Contributions of the individual ankle plantar flexors to support, forward progression and swing initiation during walking. *Journal of Biomechanics, 34*(11), 1387-1398.

Neumann, R. A. (1975). Biomechanics of the foot. In American Academy of Orthopaedic Surgeons (Ed.), *Atlas of orthotics: Biomechanical principles and application* (pp. 257-266). St. Louis: C. V. Mosby Co.

Neumann, D. A. (2010). *Kinesiology of the musculoskeletal system : Foundations for rehabilitation* (2nd ed.). St. Louis, Mo: Mosby/Elsevier.

Nigg, B. M., Nurse, M. A., & Stefanyshyn, D. J. (1999). Shoe inserts and orthotics for sport and physical activities. *Medicine and Science in Sports and Exercise, 31*, S421-S428.

Nilsson, M. K., Friis, R., Michaelsen, M. S., Jakobsen, P. A., & Nielsen, R. O. (2012). Classification of the height and flexibility of the medial longitudinal arch of the foot. *Journal of Foot and Ankle Research, 5*(1), 1-9.

Okita, N., Meyers, S. A., Challis, J. H., & Sharkey, N. A. (2013). Segmental motion of forefoot and hindfoot as a diagnostic tool.*
*. *Journal of Biomechanics, 46*(15), 2578-2585.

Park, S., & Stefanyshyn, D. J. (2011). Greater Q angle may not be a risk factor of patellofemoral pain syndrome. *Clinical Biomechanics, 26*(4), 392-396.

Perry, J., & Burnfield, J. M. (2010). *Gait analysis : Normal and pathological function* (2nd ed.). Thorofare, NJ: SLACK.

Piazza, S. J. (2005). Mechanics of the subtalar joint and its function during walking. *Foot and Ankle Clinics, 10*(3), 425-42, v. doi:10.1016/j.fcl.2005.04.001

Picciano, A., Rowlands, M., & Worrell, T. (1993). Reliability of open and closed kinetic chain subtalar joint neutral positions and navicular drop test. *The Journal of Orthopaedic and Sports Physical Therapy, 18*(4), 553.

Pohl, M. B., Messenger, N., & Buckley, J. G. (2006). Changes in foot and lower limb coupling due to systematic variations in step width. *
. Clinical Biomechanics, 21*(2), 175-183.

Powell, D. W., Long, B., Milner, C. E., & Zhang, S. (2011). Frontal plane multi-segment foot kinematics in high-and low-arched females during dynamic loading tasks.*
. Human Movement Science, 30*(1), 105-114.

Razeghi, M., & Batt, M. E. (2000). Biomechanical analysis of the effect of orthotic shoe inserts.*
. Sports Medicine, 29*(6), 425-438.

Razeghi, M., & Batt, M. E. (2002). Foot type classification: A critical review of current methods. *Gait & Posture, 15*(3), 282-291. doi:10.1016/S0966-6362(01)00151-5

Reinschmidt, C., Van Den Bogert, A. J., Lundberg, A., Nigg, B. M., Murphy, N., Stacoff, A., & Stano, A. (1997). Tibiofemoral and tibiocalcaneal motion during walking: External vs. skeletal markers.*
. Gait & Posture, 6*(2), 98-109.

Richards, C. E., Magin, P. J., & Callister, R. (2009). Is your prescription of distance running shoes evidence-based? *British Journal of Sports Medicine, 43*(3), 159-162.

Rodgers, M. M. (1988). Dynamic biomechanics of the normal foot and ankle during walking and running. *Physical Therapy, 68*(12), 1822-1830.

Roth, S., Roth, A., Jotanovic, Z., & Madarevic, T. (2013). Navicular index for differentiation of flatfoot from normal foot. *International Orthopaedics,* , 1-6.

Scott, S. H., & Winter, D. A. (1991). Talocrural and talocalcaneal joint kinematics and kinetics during the stance phase of walking. *Journal of Biomechanics, 24*(8), 743-752.

Sheehan, F. T. (2010). The instantaneous helical axis of the subtalar and talocrural joints: A non-invasive in vivo dynamic study. *Journal of Foot and Ankle Research, 3*, 13-1146-3-13. doi:10.1186/1757-1146-3-13; 10.1186/1757-1146-3-13

Spörndly-Nees, S., Dåsberg, B., Nielsen, R. O., Boesen, M. I., & Langberg, H. (2011). THE NAVICULAR POSITION TEST–A RELIABLE MEASURE OF THE NAVICULAR BONE POSITION DURING REST AND LOADING. *International Journal of Sports Physical Therapy, 6*(3), 199.

Stebbins, J., Harrington, M., Thompson, N., Zavatsky, A., & Theologis, T. (2006). Repeatability of a model for measuring multi-segment foot kinematics in children. *Gait & Posture, 23*(4), 401-410.

Stiehl, J. B., & Inman, V. T. (Eds.). (1991). *Inman's joints of the ankle* (2nd ed.). Baltimore: William & Wilkins.

Thordarson, D. B., Schmotzer, H., Chon, J., & Peters, J. (1995). Dynamic support of the human longitudinal arch: A biomechanical evaluation. *Clinical Orthopaedics and Related Research, 316*, 165-172.

Tortora, G. J., Grabowski, S. R., & Aitf_veg. (2003). *Principles of anatomy and physiology* [Atlas of the human skeleton; Exploring the functions of the human body foundations] (10th ed.). New York: Wiley.

Trimble, M. H., Bishop, M. D., Buckley, B. D., Fields, L. C., & Rozea, G. D. (2002). The relationship between clinical measurements of lower extremity posture and tibial translation. *Clinical Biomechanics, 17*(4), 286-290.

Wilken, J. M. (2006). The effect of arch height on tri-planar foot kinemetics during gait.

Williams Iii, D. S., McClay, I. S., & Hamill, J. (2001). Arch structure and injury patterns in runners. *Clinical Biomechanics (Bristol, Avon), 16*(4), 341-347.

Williams, D. S., & McClay, I. S. (2000). Measurements used to characterize the foot and the medial longitudinal arch: Reliability and validity.*
.80*(9), 864-871.

Winter, D. A. (1991). *The biomechanics and motor control of human gait : Normal, elderly and pathological* (2nd ed.). Waterloo, Ont: University of Waterloo Press.

Wong, C. K., Weil, R., & de Boer, E. (2012). Standardizing foot-type classification using arch index values. *Physiotherapy Canada, 64*(3), 280-283.

Wong, Y., Kim, W., & Ying, N. (2005). Passive motion characteristics of the talocrural and the subtalar joint by dual euler angles. *Journal of Biomechanics, 38*(12), 2480-2485.

Wrbašķić, N., & Dowling, J. (2007). An investigation into the deformable characteristics of the human foot using fluoroscopic imaging. *Clinical Biomechanics, 22*(2), 230-238.