Measuring Structural and Functional Characteristics of the Medial Longitudinal Arch: Building a Classification System

by

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Abstract

Historically, foot type has been classified on a single, linear continuum ranging from flat, to normal, to high, with minimal distinction made between differences in the medial longitudinal arch (MLA) orientation in different postures or tasks. Structural arch data has been recorded in various static positions, but functional assessment typically relies on methodologies that are difficult to replicate en mass. Because of this, a classification scheme that independently evaluates structural and functional foot arch characteristics using a simple field tool is required. A mirror box unit was used to record images of participant's footprints while they were in a sitting, standing, and partial squat position in order to progressively deform the MLA. Differences in Arch Index scores from the weighted (standing and partial squat) and unweighted (sitting) position were used to determine MLA function. Observable changes between positions were detected, indicating that functional arch type can be measured using quasi-static techniques. Accounting for both structural and functional arch characteristics will allow practitioners to be more targeted when training or treating individuals in the future. The methodology used in this study also showed that MLA deformation is impacted by body position, thus requiring standardized protocols for future data collection if results are to be considered comparable going forward.

Key words: Medial Longitudinal Arch, Foot type, Arch Index, Structural and functional

Preface

This thesis is an original work by Sydney Schmidt. The research project, of which this thesis was a part, received research ethics approval from the University of Alberta Research Ethics Board under the name "Measuring Structural and Functional Characteristics of the Medial Longitudinal Arch: Building a Classification System", No Pro00068259, approved October 12, 2016. All participants provided written informed consent.

Acknowledgements and Dedication

I would like to thank my supervisor, Dr. Loren Chiu, for his guidance, knowledge, and support throughout this research project. I would also like to acknowledge and thank the individuals who volunteered their time to participate in my thesis project. Without them, this would not have been possible.

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Chapter 1: Introduction

Introduction

Background

Structural and functional characteristics of a person's foot can be described by foot arch type. Historically, arch type classification has focused primarily on anatomical, or structural characteristics, with minimal distinction made between differences in overall movement, or function, of the foot (Arangio, Chen, & Salathe, 1998; Okita, Meyers, Challis, & Sharkey, 2013; Papuga & Burke, 2011). Because of evidence linking certain foot arch types to increased injury risk (Burns, Keenan, & Redmond, 2005; Czerniecki, 1988), it is important to understand the anatomy and mechanics underlying foot arch types in order to either prevent or better manage foot-related problems. Reliance on structural data has led practitioners to assign a functional rating of a neutral, overpronating, or under-pronating foot, which increased the likelihood of accordingly placing individuals in specific types of shoes. As the relationship between foot arch type, shoe type, and injury rates is minimal (Richards, Magin, & Callister, 2008; Nigg, Hintzen, & Ferber, 2006), industry created through training and rehabilitation programs, as well as athletic footwear and orthotic design can benefit from increased knowledge relating to the functional movement characteristics of different foot types.

The structural, or anatomical arch, is primarily measured when full body weight is applied during a static period; how the arch deforms after a force is applied, known as the functional arch, can be evaluated during dynamic movements (Nilsson, Friis, Michaelsen, Jakobsen, & Nielsen, 2012). Despite the existence of well-identified structural and functional differences, there is a lack of standardization for classifying an individual's structural and functional foot arch types (Cavanagh & Rogers, 1987; Wong, Weil, & de Boer, 2012). Arch measurements can be obtained either by indirect methods such as using footprint imaging, or directly through MRI, fluoroscopy, or three-dimensional (3D) motion analysis. While more accurate information relating to bony structures and inter-segmental movements within the foot are provided through direct methods, these techniques can be invasive, expensive, and are overall not generally accessible (Okita, Meyers, Challis, & Sharkey, 2013). Indirect measurements are typically only measured from one, static position and therefore do not provide an overall characterization of the foot.

Historically, foot arch type has been classified on a single, linear continuum ranging from flat, to normal, to high. Flat arches are associated with being flexible, collapsing under applied force, while high arches are considered rigid and do little to aid in energy absorption (Mathieson, Upton, & Birchenough, 1999). These definitions assume that structural and functional characteristics are synonymous; however, recent research suggests that this is not the case (Stamm & Chiu, 2015). A high arch, for example, may be rigid or flexible, depending on how the longitudinal arch (LA) changes during function. Because of this, a classification scheme that independently evaluates structural and functional foot arch characteristics is required.

Motivation

Though many studies have investigated techniques used to measure foot arch types, few have acknowledged potential effects of the foot and body position. The primary purpose of this study was to develop objective metrics to determine: 1) structural foot arch types, and 2) functional foot arch types using a series of static images. A secondary objective of this study was to examine structural and functional foot arch types in a large sample of healthy adults. This research will allow future studies to be conducted that examine how structural and functional foot arch types influence lower extremity bone and soft tissue loading, whether repeated biomechanically similar tasks influence foot arch types, and the association between injury patterns with foot arch types. Moreover, this information can also be used to establish a standard measurement system to non-invasively measure foot arch characteristics and may be useful in developing training or rehabilitation programs, and footwear specific to foot arch type.

Scope

In an attempt to measure both structural and functional arch types using a modified mirror box, this study used a quasi-static approach to investigate the differences between an individual's structural arch in positions selected to progressively evoke calcaneal plantar flexion, which will potentially lengthen the intrinsic muscles in the foot thereby decreasing the MLA height (Kelly, Kuitunen, Racinais, & Cresswell, 2012). The independent variable of this study was the position the foot was measured in, while the dependent variable(s) were the contact area of the foot and subsequent characteristics of the arch that could be calculated from each stationary image. The Staheli Index and Chippaux-Smirak Index (Papuga

& Burke, 2011; Queen, Mall, Hardaker, & Muley, 2007), arch angle (AA), which is also recognized as footprint angle or Clarke's angle (Clarke, 1933; Razeghi, 2002), and arch Index (AI) (Cavanagh & Rogers, 1987; McCrory, Young, Boulton, & Cavanagh, 1997) have all been found to be reliable, though imperfect, measures of structural arch measurements and were calculated during data analysis. The Staheli and Chippaux-Smirak Indices find the ratio between the narrowest part of the midfoot, and the widest part of the rearfoot and forefoot respectively. Footprint angle measures the angle between the line created by the most medial parts of the metatarsal and calcaneal regions, and the line created between the most lateral part of the medial side of the foot and the medial metatarsal area, while AI compares the area of the midfoot, to the area of the total footprint. Please refer to the literature review for a more detailed explanation of these techniques.

Participants were members of the general university population sampled at convenience and recruited at the University of Alberta, MacEwan University and the Northern Institute of Technology (NAIT). No participants were excluded from this study based on their foot arch characteristics, as a broad spectrum of structural and functional arch combinations were desired. Participants with previous injuries to the foot, such as plantar fasciitis or previously fractured tarsal, metatarsal, or phalangeal bones were excluded. The protocol developed to ensure standardization of measurements is detailed in the Methods section of this thesis.

Limitations

A major limitation of this study results from the lack of standardization relating to the measurement of foot arch characteristics, specifically with respect to the functional arch. Though the AI, and more recently Staheli and Chippaux-Smirak indices have been shown to have high inter- and intra-rater reliability when measuring structural characteristics of the arch (Papuga & Burke, 2011; Queen, Mall, Hardaker, & Muley, 2007), no consensus has yet been reached regarding their abilities to measure the foot arch as it changes during dynamic tasks. An additional limitation due to lack of standardization is the manner in which static footprints are collected; though researchers base their measurements off of an image of a footprint, it is rarely made clear whether an individual was sitting, standing with bodyweight evenly distributed between two feet, or balancing with full bodyweight placed on one foot during data collection. The lack of a gold standard for measuring foot arch characteristics limits comparisons to previous research. This study aimed to address these issues and create a standardized methodology for collecting and measuring footprint data.

As a convenience sample consisting primarily of college and university students and staff was employed, and data was collected in locations near fitness facilities on campuses, the study population was likely not representative of the general population. This may limit the overall generalizability of results due to a lower average age of participants, and individuals may have more muscular body compositions due to the location of data collection. However, research from Menz (2015) and Bertani et al (2017) indicate that arch characteristics do not significantly differ from the average healthy adult before age 60, so this study imposed a conservative limit of 55 years to mediate this issue. Research indicates that individuals with a body mass index (BMI) above 30.0 are more likely to display pes planus (flatter) structural arch characteristics, so an initial BMI limitation of 29.9 was imposed. In order to ensure that results closely resembled a healthy adult, the BMI cutoff was set at 26.0, which was within the range of elite and varsity athletes competing in a variety of sports (Niekoladis, 2014; Gerodimos, Manous, Kellis, & Kellis, 2005; Stanforth, Crim, Stanforth, & Stults-Kolehmainen, 2014).

Definitions

Plantar flexion and dorsiflexion are used to describe sagittal plane motion of bones in the foot and ankle complex. Ankle joint plantar flexion occurs when the rearfoot rolls forward relative to the leg or the leg rotates backwards relative to the rearfoot, resulting in a net increase in the angle between the leg and the foot on the anterior surface (Neumann, 2013). In contrast, dorsiflexion is the net decrease in the anterior angle between the foot and leg. Specific to bone motion, calcaneal plantar flexion occurs when the calcaneus rolls forward relative to the global coordinate system. Plantar surface refers to the inferior portion of the foot.

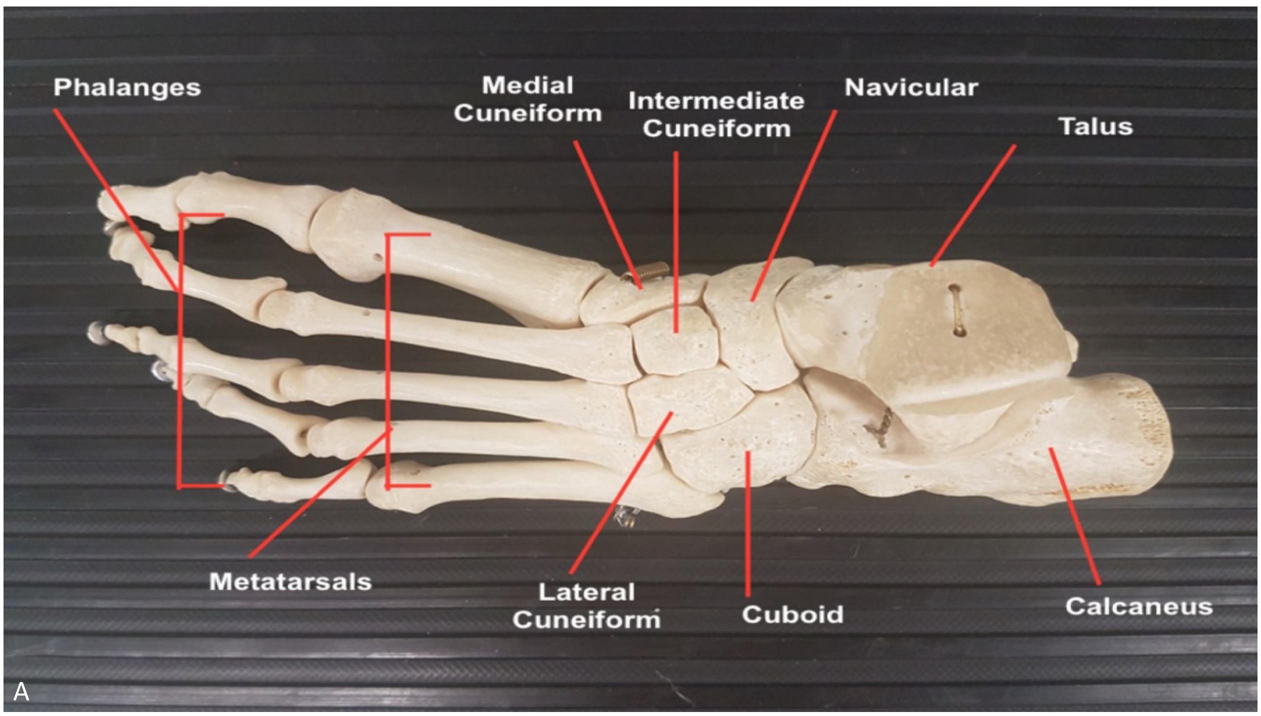
The overall foot arch is comprised of three individual arches: the transverse arch running horizontally across the metatarsal bones, the lateral longitudinal arch on the lateral side of the foot, and the medial longitudinal arch (MLA) on the medial side, which function collectively to disperse and transmit forces evenly throughout the foot (Neumann, 2013). The MLA is the primary arch this study makes reference to. Arch structure refers to the overall shape or height of the MLA, and arch function refers to its movement relative to the amount and direction of force applied. There are three commonly identified structural arch types; a pes cavus foot has a high arch shape, a normal, or pes rectus, foot has a medium arch height, and a pes planus foot has a low arch height. Typically, when force is applied to the MLA, the overall structural arch height decreases or flattens, and presents as increased plantar contact area in images. The structural arch is considered to be raised when the MLA moves further away from the ground and typically occurs due to a reduction of external forces.

The primary metrics that will be used to measure the overall structural foot arch type will be: AI, Staheli Index, Chippaux-Smirak Index, and AA. These metrics will be discussed in more detail in the Literature Review.

Literature Review

Foot Bony Anatomy

The foot is comprised of 7 tarsal bones (talus, calcaneus, navicular (medial), cuboid (lateral), and 3 cuneiforms), 5 metatarsals (toes), and 14 phalanges (end toe segments) as seen in Figure 1-1. Though the foot has historically been analyzed as one rigid body, studying fine motor movements between the individual structures in the foot have thus rendered it necessary to break the foot into segments for a multi-segmental approach (Kelly, Cresswell, Racinais, Whiteley, & Lichtwark, 2014). The midfoot is a primary section of interest when studying the foot arch, and is formed by the navicular, cuneiforms, and cuboid bones. The forefoot is comprised of the metatarsals and phalnges, and the rearfoot is comprised of the talus and calcaneal bones.



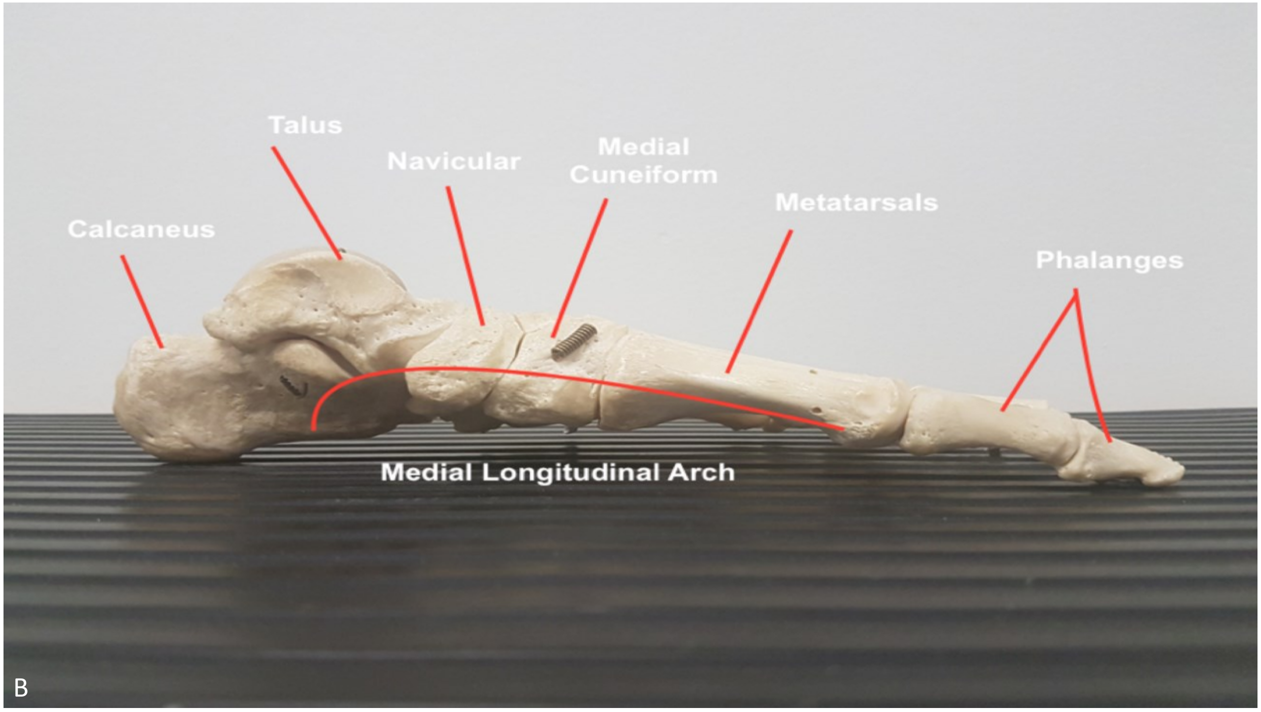


Figure 1-1: Bones in the foot from a superior (A) and medial (B) view point

The rest of the body articulates with the foot via the leg segment (tibia and fibula) at the talus at the talocrural joint, forming a mortis joint, allowing one degree of freedom in the sagittal plane (Neumann, 2013). This is recognized as plantarflexion, an increasing anterior angle between the tibia and talus, and dorsiflexion, a decreasing angle between the tibia and the talus, at the talocrural joint. The tibia is the larger of the bones in the leg segment and has an irregular articulating surface, resulting in the majority of forces passing through the talo-tibial portion of the joint. Rotation occurs around transverse axis, which passes imperfectly through the medial and lateral malleoli. This offset translates into multi-planar motion, with slight adduction and inversion occurring with plantarflexion, and abduction and eversion occurring with dorsiflexion (Wong, Kim, & Ying, 2005). The anterior surface area of the tibia is wider and therefore prevents excessive anterior gliding of the leg relative to the talus; this limits dorsiflexion to an average of 26° and increases the overall stability of the joint (Neumann, 2013).

The subtalar joint is the articulation between the inferior surface of the talus and three dorsal facets of the irregularly shaped calcaneus (Neumann, 2013). The posterior calcaneal facet is convex and the most prominent relative to the anterior and middle facets; this shape improves joint congruity and acts in combination with surrounding musculature and ligaments to increases the overall support and stability of the joint. The primary movements occurring at the subtalar joint are inversion (23°) and eversion (13°) of the calcaneus, however, imperfect alignment of the axis of rotation allows for multiplanar joint movement. It is thought that calcaneal eversion contributes to decreasing MLA height, but overall motion at the subtalar joint is thought to be limited relative to the talocrural joint, especially during weightbearing tasks (Hamel, Sharkey, Buczek, & Michelson, 2004), which often result in the calcaneus and talus acting in tandem during plantarflexion. However, Chizewski and Chiu (2012) demonstrated independent calcaneal plantar flexion, which contributes to overall plantar flexion of the ankle, and potentially contributes to a decrease in MLA height.

The bones in the foot jointly form the transverse arch, and the medial and lateral longitudinal arches, which collectively support the foot both statically and dynamically. The MLA is the primary load-bearing and shock-absorbing structure in the foot, and is comprised of the calcaneus, talus, navicular, cuneiforms, and associated 3 metatarsals as shown in Figure 1-1b (Neumann, 2013). This study focused primarily on the MLA. The bony structures alone can generally support the foot during periods of low-stress, but muscular support is required to accommodate more dynamic loads, such as those experienced while walking or running (Martini, Timmons, & Tallitsch, 2005). While standing, body weight is typically dispersed through the talonavicular joint, where the MLA distributes the forces anteriorly and posteriorly to the fore-and rearfoot respectively. As the talus depresses inferiorly, the MLA will flatten. Shifting body weight or unloading the foot allows the arch to return to its preloaded, raised height.

Foot Soft Tissue Anatomy

There are several groups of muscles that are important to consider when analyzing movement in the foot and ankle as they aid in lower extremity shock absorption and contribute to static and dynamic control. There are no muscles that directly cross the subtalar joint and attach to both the talus and calcaneus, meaning that muscles that directly insert onto the calcaneus indirectly contribute to subtalar motion (Neumann, 2013). Extrinsic muscles that insert into the bones in the foot, such as the soleus, gastrocnemius, or tibialis anterior and posterior, contribute to the gross movements occurring at the foot if the leg and thigh are fixed. The tibialis anterior inserts onto the medial cuneiform and metatarsal bones, and in addition to stabilizing the ankle, contribute to dorsiflexion and inversion of the foot. Tibialis posterior contributes to inversion and plantar flexion when the leg is fixed and inserts on to the navicular and medial cuneiform. The gastrocnemius assists in flexion at the knee, and together with the soleus, have a common attachment onto the calcaneus via the calcaneal (Achilles) tendon, contributing to plantar flexion. If the leg is fixed, leaving the calcaneus free to rotate, the collective pull on the calcaneus by the plantar flexors will cause it to slide posteriorly relative to the talus at the subtalar joint, resulting in net calcaneal plantar flexion (Martini, Timmons, & Tallitsch, 2005). This calcaneal plantar flexion will in turn pull on the plantar aponeurosis, which will raise the MLA as the toes are pulled posteriorly towards the calcaneus.

A change in position of the calcaneus due to activation of the gastrocnemius, soleus, or other posterior plantar flexors can also impact the tiny, plantar intrinsic muscles that attach to the distal aspect of the calcaneus. These muscles help with postural and balance control, and distribution of forces in the foot (Neumann, 2013). Though it was previously assumed that the intrinsic muscles such as abductor hallucis, flexor digitorum brevis, and quadratus plantae were only activated as a secondary support mechanism to help accommodate large forces experienced during gait, Kelly *et. al* (2012, 2014) have observed muscle unit lengthening during more static periods, including while standing or at rest. As these muscles had typically been deemed largely irrelevant in contributing to MLA function, these findings suggesting more chronic activity of the intrinsic muscles could indicate a contribution to long-term structural as well as functional changes in the foot arch.

The plantar aponeurosis is a thick band of fibrous connective tissue with proximal attachment onto the calcaneal tuberosity and distal attachments at the metatarsal heads (Neumann, 2013). These fibres align in both anterior-posterior and medial-lateral directions and contribute to shock absorption and the overall support of the foot. The plantar aponeurosis stretches when the MLA deforms under a load, and shortens to exert a force directed on the metatarsal heads towards the calcaneus shortens in order to increase support and raise the height of the MLA during calcaneal plantar flexion or dorsiflexion of the toes (Arangio, Chen, & Salathe, 1998).

Foot Arch Types

Foot arch types are classified by either their structural or functional characteristics and are not typically classified by both measures independently. Structural differences between foot types are the result of bony structural differences, while differences in musculature, ligaments and other soft tissue structures in the foot and ankle joint complex contribute to functional variations (Caravaggi, Pataky, Goulermas, Savage, & Crompton, 2009). Though there are many documented methodologies for measuring the structural arch, the differences in the functional arch can only be found when comparing the non-weightbearing foot to the weightbearing one. Through exercise, it is possible that functional characteristics of the foot can be changed, but it appears that little can be done about structural characteristics in the adult foot.

The foot arch types that are commonly referred to in the literature are based on the structural arch. Pes cavus, or high-arched feet, are typically associated with excessive rearfoot inversion and can experience functional limitations ranging from none to marked as a result (Neumann, 2013; Jenkyn, Shultz, Griffin, & Birmingham, 2010; Okita, Meyers, Challis, & Sharkey, 2013). Simply stated, these limitations can prevent the foot from optimally absorbing impact forces during gait, which therefore increases susceptibility to stress-related injuries in the foot or lower limb. In contrast, a pes planus foot, presents as a flatter or lower arch shape when compared to the normal (pes rectus) foot (Wolf, et al., 2008; Cavanagh, et al., 1997). There is typically a greater degree of functional variability observed in pes planus feet. A rigid pes planus foot experiences a compromised ability to dissipate loads and therefore require a lot of intrinsic and extrinsic muscle activity to help support the lack of tension in the arch. A flexible pes planus foot is more commonly observed, where the MLA appears normal while unloaded, but drops excessively when weight bearing. Overuse injuries and overall laxity in the connective tissues result in excessive calcaneal eversion (medial side of foot), which contributes to excessive subtalar pronation (Neumann, 2013).

As structural variations in the foot have been observed, it follows that there are functional differences between foot arch types as well. The primary functions of the MLA are load-bearing and shock-absorption in the foot, which when functioning normally, help facilitate a larger range of force absorption than would typically be tolerated by the tarsal bones (Neumann, 2013). At rest or during low-impact movements, the bones and connective tissues in the MLA are typically thought to be sufficient to support the foot, however movements generating higher impact forces, such as jumping or running, require activation of the intrinsic muscles in the foot. This intrinsic muscle activity has been shown by Kelly *et al.* (2014) during static periods and by Kido *et al.* (2013) when the foot was taken through progressive loading. As of now, the correlation between intrinsic muscle activation patterns and functional foot arch type has been relatively unexplored and will require future research.

In a normally functioning foot, weight bearing will cause deformation of the MLA, which is facilitated by inter-segmental rotations between the proximal and distal bones in the arch, as well as from surrounding soft tissues (Wolf et al, 2008). When functioning effectively, the foot arch rises and remains domed in order to help stabilize the foot as a force is applied. The plantar aponeurosis is of particular importance for proper foot arch functioning (Hicks, 1954; Neumann, 2013). The plantar aponeurosis helps support the foot by employing the windlass mechanism, whereby dorsiflexing the first toe at the metatarso-phalangeal joint acts as a drum in a pulley system and increases the tension in the facia. This causes the length of the fascia to shorten and pulls the calcaneus anteriorly to raise the MLA. Using both living and cadaveric foot models, Hicks showed this mechanism effectively raised the arch height without additional muscular activity, and that the amount of dorsiflexion is related to the arch height increase (1954). Kappel-Bargas *et al.* (1998) furthered this research by finding distinct subpopulations with either immediate- or delayed-onset of the mechanism, meaning that in some feet, less dorsiflexion of the first toe is required to immediately raise the MLA, suggesting greater tensile forces in the plantar aponeurosis. Kappel-Bargas *et al.* also found increased rearfoot eversion in the delayed-onset group, indicating decreased midfoot stabilization and a more flexible foot arch. Increased inelasticity of the plantar aponeurosis has been correlated to reduced foot mobility, as well as plantar fasciitis and heel pain (Sahin, Ozturk, & Atici, 2010).

Measurement of Foot Arch Type

There is a lack of standardization when attempting to classify a foot based on both structural and functional characteristics. Though most studies have not found significant structural or functional differences between genders (Queen, Mall, Hardaker, & Muley, 2007; Sporndly-Nees, Dasberg, Nielsen, Boesen, & Langberg, 2011), differences in foot arch characteristics have been identified between left and right feet in the same individual (Nilsson, Friis, Michaelsen, Jakobsen, & Nielsen, 2012). Age is another important consideration when attempting to standardize classification. A pes planus foot is more commonly observed in elderly individuals due to decreased muscular strength and increased soft tissue stiffness (Menz, 2015; Goonetilleke R. S., 2013). This in turn decreases overall joint mobility and results in a more pronated foot position. Overtime, this can cause foot pain and alter gait mechanics (Bertani, M, Doares, D, Rocha, E, & Machado, L, 2017). Body mass index also impacts an individual's structural arch characteristics. Domjanic *et al.* (2015), Wearing *et al.* (2012) , and Ku *et al.* (2012) have all found that an increase in an individual's BMI correlated to increased foot width and an overall decrease in arch height. Specifically, individuals with increased adipose tissue and BMIs over 30.0 had decreased postural foot control resulting in flatter arches that could not be attributed to bony alignment of the tarsal bones.

Different methodologies have been developed in an attempt to capture both structural and functional arch characteristics using both direct and indirect measures. Indirect measures are typically image-based and rely on footprints (Cavanagh & Rogers, 1987), mirror boxes (Queen, Mall, Hardaker, & Muley, 2007), or foot casting (Nilsson, Friis, Michaelsen, Jakobsen, & Nielsen, 2012). Images are primarily taken in static rather than dynamic positions, making the results difficult to apply to functional components of the foot. As previously mentioned, discrepancies in measurement positions exist with respect to weightbearing or non-weightbearing, further complicating comparisons of structural arch types. 3D photographic scans (Reinschmidt, et al., 1997), fluoroscopy (Wrbaškić & Dowling, 2007; Shultz, Kedgley, & Jenkyn, 2011; Wearing, et al., 2005), and MRI (Rugg, Gregor, Mandelbaum, & Chiu, 1990) all allow for direct measurement of foot arch characteristics, but participant numbers in these studies are limited due to complicated methodologies.

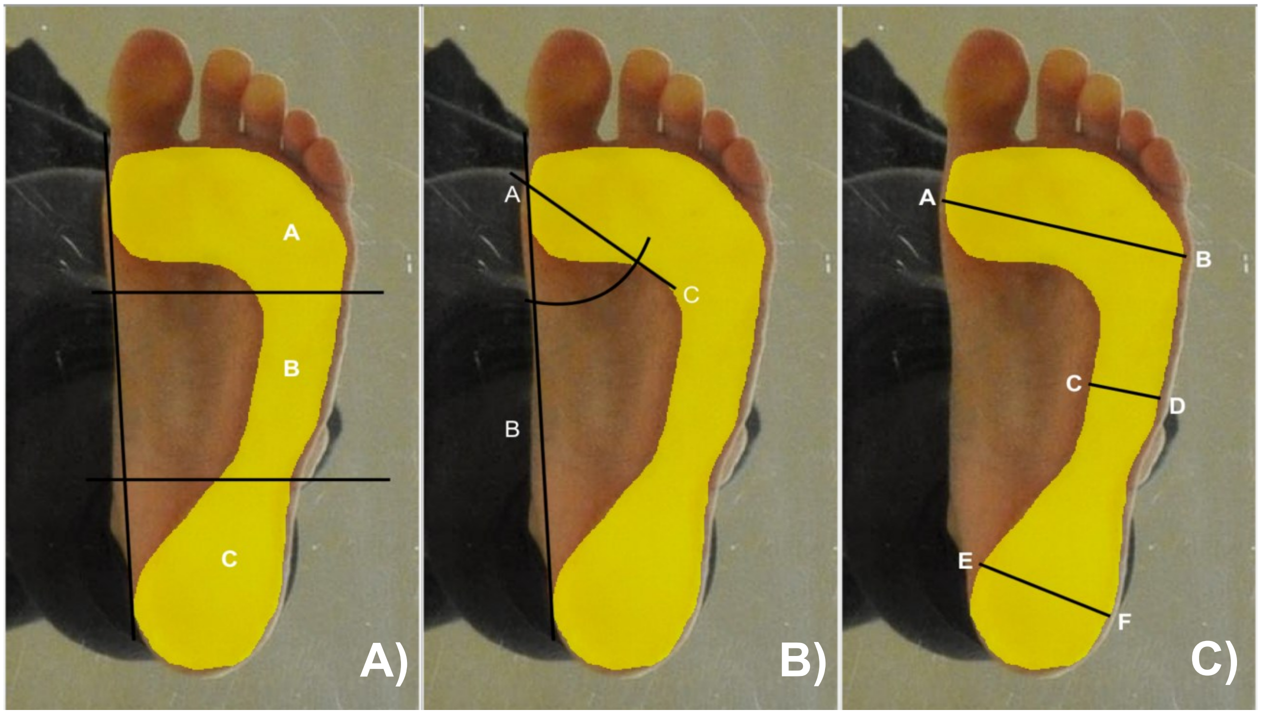


Figure 1-2: Diagram showing various methods for calculating foot arch characteristics; a) Arch Index (B/(A+B+C)). b) Footprint Angle. c) Staheli Index (CD/EF) and Chippaux-Smirak Index (CD/AB).

Measuring Structural Foot Arch

Until recently, the Arch Index method was the most common method used to classify the foot arch type (Cavanagh & Rogers, 1987; Queen, Mall, Hardaker, & Muley, 2007). A footprint image from the subject taken while standing, walking, or running, is divided into thirds (Figure 2C). The midfoot area is identified as the middle third of the foot. This area is then found and compared to the total area of the foot, giving in a percentage referred to as the Arch Index. Normal feet have AI values ranging from 0.21-0.26. Values scoring below 0.21 are considered to have high arches, and anything greater than 0.26 is considered a flat arch. The AA technique similarly uses a footprint image to classify arch types. As seen in Figure 2B, an angle is formed between the line created by the most medial parts of the metatarsal and calcaneal regions, and the line created between the most lateral part of the medial side of the foot and the medial metatarsal area. A normal arch measures between 31.22-52.88° with decreasing angles indicating a flattening of the MLA as the midfoot area widens (Clarke, 1933). The Staheli and Chippaux-Smirak indices are shown in Figure 2D. These indices use ratios between the narrowest part of the midfoot, and the widest parts of the fore- (Chippaux-Smirak) and rearfoot (Staheli) (Papuga & Burke, 2011). These indices provide a simple way to calculate data using footprint images and have high inter-rater correlation scores (0.96 for both). A normal foot scores between 0.471-0.893 using the Chippaux-Smirak Index and between 0.60-1.09 with the Staheli Index. Other methods, such as calculating navicular drop (position of the navicular bone) are limited because they only provide information relating to the foot arch in one plane of motion (Sporndly-Nees, Dasberg, Nielsen, Boesen, & Langberg, 2011).

Table 1-1: Static arch measurement comparisons

Test	Variable	Mean	Pes Cavus & Pes Planus	Reliability
Arch Index (Cavanagh & Rogers, 1987; Razeghi, 2002)	$\frac{\text{area of midfoot}}{\text{area of footprint}}$	0.23 SD ± 0.046	Cavus: ≥ 0.26 Planus: ≤ 0.21	70-97%
Arch Angle (Clarke, 1933; Razeghi, 2002)	angle between medial length of foot and the line between anterio-medial aspect of MLA	42.05° SD ± 10.83°	Cavus: ≤ 31.22° Planus: ≥ 52.88°	81-97%
Chippaux-Smirak Index (Mathieson, Upton, & Birchenough, 1999; Queen, Mall, Hardaker, & Muley, 2007)	$\frac{\text{narrowest part of the midfoot}}{\text{widest part of the forefoot}}$	0.68 SD ± 0.21	Cavus: ≥ 0.47 Planus: ≤ 0.89	96%
Staheli Index (Mathieson, Upton, & Birchenough, 1999; Queen, Mall, Hardaker, & Muley, 2007)	$\frac{\text{narrowest part of the midfoot}}{\text{widest part of the rearfoot}}$	0.85 SD ± 0.24	Cavus: ≥ 0.61 Planus: ≤ 1.09	96%

Measuring Functional Foot Arch

Static measures of foot arch types are typically poorly correlated to functional foot arch types (Razeghi and Batt, 2002; Kaufman, Brodine, Shaffer, Johnson, & Cullison, 1999). As many soft tissues supporting the MLA are passive while static or in non-weight bearing positions, their contribution to foot arch functioning may be missed, yielding an incomplete picture of foot arch type. Methodologies providing accurate functional arch characteristics are typically invasive and require access to an MRI machine or full laboratory set up, but they allow arch data to be collected while performing dynamic tasks. Wrbaškić and Dowling (2006) used fluoroscopy, skin markers, and a pressure sensor to better understand loading and unloading properties of the foot. Participants performed a one-footed jump, lifted themselves onto their toes before lowering back down to their heel, and contacted the sensor with only their toes and ball of the foot in order to mimic jumping, walking, and running. These data examined when and where foot rigidity was maintained throughout tasks and reinforced the need to use a multi-segmental model of the foot. Reinschmidt *et al.* (1997) attempted to directly measure in vivo skeletal motion while walking using markers drilled directly into bone, in combination with external skin markers. They found that peak calcaneal plantarflexion, which increases MLA height and support, occurred around heel strike during loading response in the stance phase. These results are supported by Okita *et al.* (2013), Hamel *et al.* (2004), and Bruening *et al.* (2012).

Research performed with lower extremity cadavers have been helpful when attempting to understand soft tissue contributions to functional MLA characteristics. It has been shown that manipulating activation levels of supporting soft tissue structures such as tibialis posterior, plantar aponeurosis, and intrinsic muscles such as abductor hallucis, flexor digitorum brevis and quadratus plantae can influence the height of the MLA (Kelly, Cresswell, Racinais, Whiteley, & Lichtwark, 2014; Okita, Meyers, Challis, & Sharkey, 2013; Arangio, Chen, & Salathe, 1998). The cadaveric models can be tested using force plates and 3D-motion analysis, computed tomography (CT) scans, or MRI scans, with data being used to generate 3D computer models. Prior to studies by Kelly *et al.* (2011, 2014, 2015), intrinsic musculature was typically thought to activate in order to assist foot flexors during toe-off in gait or during periods of increased loading. Electrical stimulation shows that these muscles activate earlier than anticipated and have the capacity to control deformation of the MLA, even during static periods. By increasing the understanding of factors contributing to the deformation of the MLA, better comparisons can be drawn between structural arch characteristics captured at specific moments and the overall functioning of the MLA.

Researchers have attempted to infer functional arch characteristics using static data. Cavanaugh and Rogers (1987) tested participants in a static, walking, and running positions, and found a mean maximal change of 9.6% in dynamic AI scores from the static baseline, indicating a decrease in MLA height. The static data was collected in a half body weight position, meaning that the participant was standing with weight equally distributed between two feet. These results are problematic as the change in AI scores ranged from -15.4% to 39.6%, and the study only had 10 participants. Mathiseon *et al.* (1999) followed a similar methodology with 20 participants comparing AA and Staheli and Chippaux-Smirak indices between static and dynamic positions. Arch angle reliability was found to be too low, however, Staheli and Chippaux-Smirak were shown to have increased 28.0% and 25.6% respectively. These two indices were highly correlated between static and dynamic position, indicating that statically calculated footprint indices may infer some dynamic characteristics. Again, as this study was underpowered, determining functional characteristics using footprints collected in static and dynamic situations requires more research. Absence of an absolute measurement tool has led to variation in the choice of metrics used when attempting to determine structural and functional arch characteristics thus making it difficult to compare results between studies, again reinforcing the need for a valid classification system.

Conclusion

While each methodology has attempted to contribute to the overall classification of the arch, there inevitably are weaknesses that need to be addressed. Direct measures provide the most accurate measures in the foot, but they are expensive and potentially harmful long-term to individuals. This limits the use of any classification information they might provide as it is not practical to apply these methodologies en masse. Indirect measures are much less time-consuming to perform, making them easily accessible to the general public; however, because images are typically only taken in one position – be it static or dynamic – the overall picture of structure and function has yet to properly be generated. It is also important to establish set postural positions with respect to the amount of bodyweight placed on the foot when collecting static footprints. A quasi-static approach comparing a series of static measures within one foot to may help fill this gap. As the foot is taken through a range of motions chosen to progressively deform the arch, both structural and functional data can be obtained.

Purpose Statement

This study will attempt to establish a classification system of healthy, adult feet in order to determine both structural and functional arch characteristics using a non-invasive technique. This is a relational study comparing static MLA measurements obtained through a series of footprint images, with special care being taken to ensure proper lower body placement and bodyweight distribution is achieved in each of the selected positions.

Hypothesis

Based on current literature and pilot research, this study hypothesized that measuring structural arch footprints under different loading conditions would showcase the functional range of the MLA, thereby combining and refining current classification methodologies into one standardized system providing complete information about an individual's foot. Specifically, weight bearing might cause MLA deformation compared to non-weight bearing positions, therefore, change in an arch footprint from non-weight bearing to weight bearing will indicate functional arch type. Because of this, it is important to standardize the body and leg position during structural arch data collection.

Chapter 2: Classifying Structural and Functional Arch Characteristics Through a Series of Static Images

Introduction

Kinetic Chain and Injuries

Approximately 25% of the bones in the body are located in the feet, and when properly aligned and supported by soft tissue, allow an individual to efficiently perform an array of physical tasks in a variety of environments. When weightbearing, healthy feet act as the base of the human kinetic chain, permitting the properly alignment and functioning of lower extremity and rest of the body (Kirby, 2000). Musculoskeletal injuries to the foot and ankle can therefore present as a significant public health challenge that will likely increase as the population ages. Common injuries to the foot include plantar fasciitis, metatarsal fractures, rheumatoid and osteoarthritis, metatarsalgia, stress fractures and turf toe (Chinn and Hertel, 2011; Lysholm and Wiklander, 1987; Sobhani, Dekker, Postema, and Dijkstra, 2013). These injuries can not only cause physical pain and disability, but also impact and individual's ability to perform essential activities of daily living such as walking.

Abnormal functioning of the foot often translates to misalignment of the rest of the body. This can contribute to additional injuries at the ankle, knee or hip, and places older adults at an increased risk of falling (Cavanagh, Morag, Boulton, Young and Deffner, 1997; Rao, Riskowski, and Hannan, 2012). As the degree of MLA deformation varies between functional arch types, common injury patterns have begun to emerge. The immobility typically associated with rigid pes cavus feet is associated with increased rates of overuse injuries, injuries at the ankle and lateral side of the foot, as well as tibial or femoral stress fractures due to less efficient force absorption from initial contact with the ground (Kaufman, Brodine, and Shaffer, 1999; Nigg, Nurse, and Stefanyshyn, 1999). Contrarily, feet with highly flexible functional arch types, commonly associated with a pes planus structual arch type, experience more injuries on the medial side of the foot or ankle, and stress fractures are more likely to occur in the metatarsals (Burns, Keenan, & Redmond, 2005;

Nigg, Nurse and Stefanyshyn). Risk of knee pain and ipsilateral hip pain are also higher with pes planus feet (Rao, Riskowski, and Hannan, 2012).

Treatment of a foot injury often relies on placing an individual in a “motion control” shoe or orthotic to not only redistribute plantar loads and restore static and dynamic foot alignment, but also improve ankle range of motion while assisting with forward propulsion or balance, depending on the type of orthoses required (Rao, Riskowski, and Hannan, 2012). Orthotics typically provide support to the rear- and medial aspect of the foot while attempting to decrease excess MLA deformation and regain proper anatomical alignment. Orthotics typically reduce muscular demands on those controlling the calcaneus by providing a physical barrier in an attempt to limit calcaneal plantar flexion, causing some practitioners to question their long-term use (Rao, Riskowski, and Hannan, 2012). The use of tape, targeted and generalized strength training, and stretching programs or manual therapy have since become key components of rehabilitation plans.

Normal Functioning of the Foot and Ankle

A properly functioning foot and ankle complex must be able to regularly absorb and translate impact forces from contact with a variety of surfaces, as well as support approximately half of an individual’s bodyweight while standing. The primary movements occurring at the talocrural joint are plantar and dorsiflexion about the imperfectly aligned transverse axis (Neumann, 2013). This imperfection results in slight adduction and inversion when plantar flexing and slight abduction and eversion when dorsiflexing. Forty-eight degrees of plantar flexion and 26º of dorsiflexion are considered to be average ranges of movement. The neutral subtalar joint also rotates about an imperfect axis; the sagittal axis is offset a reported 42º from the horizontal and 16º medial of midline though slightly different ranges have been reported (Neumann, 2013; Hicks, 1953). The primary movements at this joint are calcaneal inversion (23º) and eversion (13º) relative to the talus, however deviations allow for tri-planar motion relative to a fixed calcaneus. Inversion, adduction and plantar flexion and are collectively referred to as supination, and abduction of the forefoot, eversion of the hindfoot, and dorsiflexion collectively comprise pronation.

Augmentation of the MLA helps the foot perform motion control. Raising the height of the MLA helps to stiffen the foot, likely increasing mechanical efficiency in both static and dynamic tasks (Kelly, Cresswell, Racinais, Whiteley, & Lichtwark, 2014). In a healthy adult foot, force absorption and translation within the foot is facilitated by the Windlass mechanism. Dorsiflexion of the first toe causes calcaneal dorsiflexion due to increased tension in the plantar aponeurosis, thus raising the height of the MLA and supporting the foot (Neumann, 2013; Hicks, 1954). Decreasing MLA height may be important in tasks where ankle dorsiflexion is desirable, such as while walking (Stamm & Chiu, 2015) and squatting (Chizewski & Chiu, 2012). Understanding how calcaneal rotation may influence overall function of the MLA in weighted and unweighted conditions may allow practitioners to better utilize non-invasive field tests to classify different functional arch types.

Classification

The foot is often considered as one rigid segment, but as this model significantly downplays the effects of movements occurring between the 33 bones in the foot, a multi-segmental model breaking the foot into three or four rigid segments allows practitioners to better understand boney rotations contributing to MLA height changes (Wrbaškić & Dowling, 2007; Neumann, 2013). Being able to effectively evaluate the structural and functional characteristics of the foot is important for identifying normal and abnormal foot types. It is therefore crucial that measurements taken are comparable, which requires measurements to be recorded in like conditions. Understanding overall MLA movement and differences in deformation patterns is then useful for selecting or designing appropriate footwear for different foot types, developing treatments for abnormal foot types, and evaluating how foot type may influence injuries in the lower body. Correctly identifying MLA characteristics in different postures and tasks is therefore essential.

Multiple methods have been developed over the years that attempt to accurately assess arch type. Various ratios and angles have been found by comparing various aspects of a footprint, but glaringly, the position in which the data was captured has varied, and yet results are considered comparable. Traditionally, structural arch types are measured while standing, but weight distribution between the feet while recording data ranges from 50-90% weightbearing (Cavanagh & Rogers, 1987; Queen, Mall, Hardaker, & Muley, 2007).

Other structural baseline values are assessed in dynamic situations, where the participants with the data coming from the first step onto a pressure platform (Wearing, Grigg, Lau, & Smeathers, 2012), and some researchers did not specify body position. No baseline data was found using an unweighted footprint. All these studies used AI in order to classify arch types structurally, and many would use the initial results when attempting to classify functional arch types. As MLA height varies based on position (Cavanagh, et al., 1997), establishing a protocol to record a true structural baseline measure is essential, in order to properly assess functional characteristics.

Measurement Techniques

Scientists have been attempting to track and utilize MLA characteristics to determine an individual's foot type for over one hundred years (Cavanagh & Rogers, 1987). Arch angle, also known as footprint or Clarke's angle, was first calculated in 1928, AI and the Staheli Index in 1987, and the Chippaux-Smirak Index in 1990 and are still widely used to quantify MLA structural characteristics (Clarke, 1933; Goonetilleke R. S., 2013). These data use a recording of an individual's footprint to determine the degree of MLA deformation, and thus provide information of the structural arch characteristics. Though each of these metrics individually is able to sort a footprint into one of the pes cavus, normal, or pes planus foot types, without ensuring that the analyzed footprint is collected from a standardized position, it is difficult to definitively say that the functional characteristics of an individual with a normal footprint collected while sitting differ from a pes cavus footprint collected while an individual is standing with weight equally distributed between both feet. While being relatively simple to collect and analyze, static data does not provide complete information about an individual's functional arch type.

As previously noted, the MLA augments its shape based on kinetic demands, meaning the same foot could be classified differently depending on the conditions the static footprint was captured in. Functional arch type cannot therefore be qualified by one still footprint image and minimal correlation between static arch classification and functional arch type exists (Harris, 2010). Data collected from dynamic situations provide a more complete portrayal of MLA function, but require more involved experimental processes and analysis. Navicular drop is the simplest technique and involves recording the sagittal plane translation of the navicular tuberosity between weight bearing and non-weightbearing positions. This requires that practitioners are correctly able to identify the bony landmark as well as the neutral subtalar joint position of the starting position and does not account for possible frontal plane rotation (Razeghi and Batt, 2002). Additionally, only moderate to poor reliability has been found as navicular displacement is limited even in flexible arches. Other methodologies assessing function require access to motion capture systems, x-ray, radiographic, or magnetic resonance imaging scans. This limits regular practitioner use as these technologies are not easily accessible and often involve increased risk to participants. Quasi-static measurements modify the premise of static measurement by capturing data in a variety of functional positions. When analyzed collectively, comparisons of static scores can provide an indication of overall arch function at minimal individual risk. Establishing standardization of positions that footprints are recorded in allows results to be compared between studies.

The primary purpose of this study was to establish a classification system for both structural and functional characteristics of the arch measured using a non-invasive quasi-static technique. This provides practitioners with a simple field tool with minimal time needed for analysis to determine an individual's structural and functional arch type. The secondary objective of this study was to establish a standardized procedure for measuring structural arch types, thus ensuring calculated metrics are comparable between studies. Doing so will establish a baseline protocol that future studies may use when using foot type data to investigate mechanics and injury patterns, or footwear and orthotic design.

Methods

Experimental Design

Using a case-control study design (Trochim & Donnelly, 2001), men and women (ages 18-55) with healthy feet were recruited in order to have photographs of their footprints taken for further analysis while they were sitting, standing, and in a partial squat. Arch Index, AA, and Staheli and Chippaux-Smirak Indices were selected as metrics to be used in the subsequent analysis as they are commonly used to classify structural foot arch types and have high reliability scores. It is appropriate to compare body position during measurement with the different foot arch characteristics chosen, as this study aimed to note changes in these measurements in order to determine functional foot arch types. It was also important to set standard protocols so that future MLA scores may accurately be compared. Comparing data between the left and right sides of the body may provide insight into structural or functional characteristics related to foot dominance.

Participants

Two hundred and five individuals (female: n=115; male: n=85) volunteered to participate in this research study. This study was approved by the University of Alberta's Research Ethics Board (No Pro00068259), and written informed consent was required prior to data collection. Potential participants were recruited as a convenience sample through recruitment presentations conducted in various undergraduate laboratories and lectures in the Faculty of Kinesiology, Sport, and Recreation at the University of Alberta, as well as through the use of posters placed throughout the campuses of the University of Alberta, MacEwan University, and NAIT. An upper age limit of 55 years was placed on participants in order to mitigate any potential age-related foot problems, and participants were excluded if their BMI exceeded 26.0, or if they had sustained any injuries to their feet. Of the 205 participants, 150 people had data collected on both feet, three people only had data collected on their left foot, and five only had data collected on their right foot, for a total of 158 participants. Because previous research has not determined significant differences between left and right feet, it was appropriate to collect data on the healthy foot of individuals with disqualifying injuries on only one side of their body.

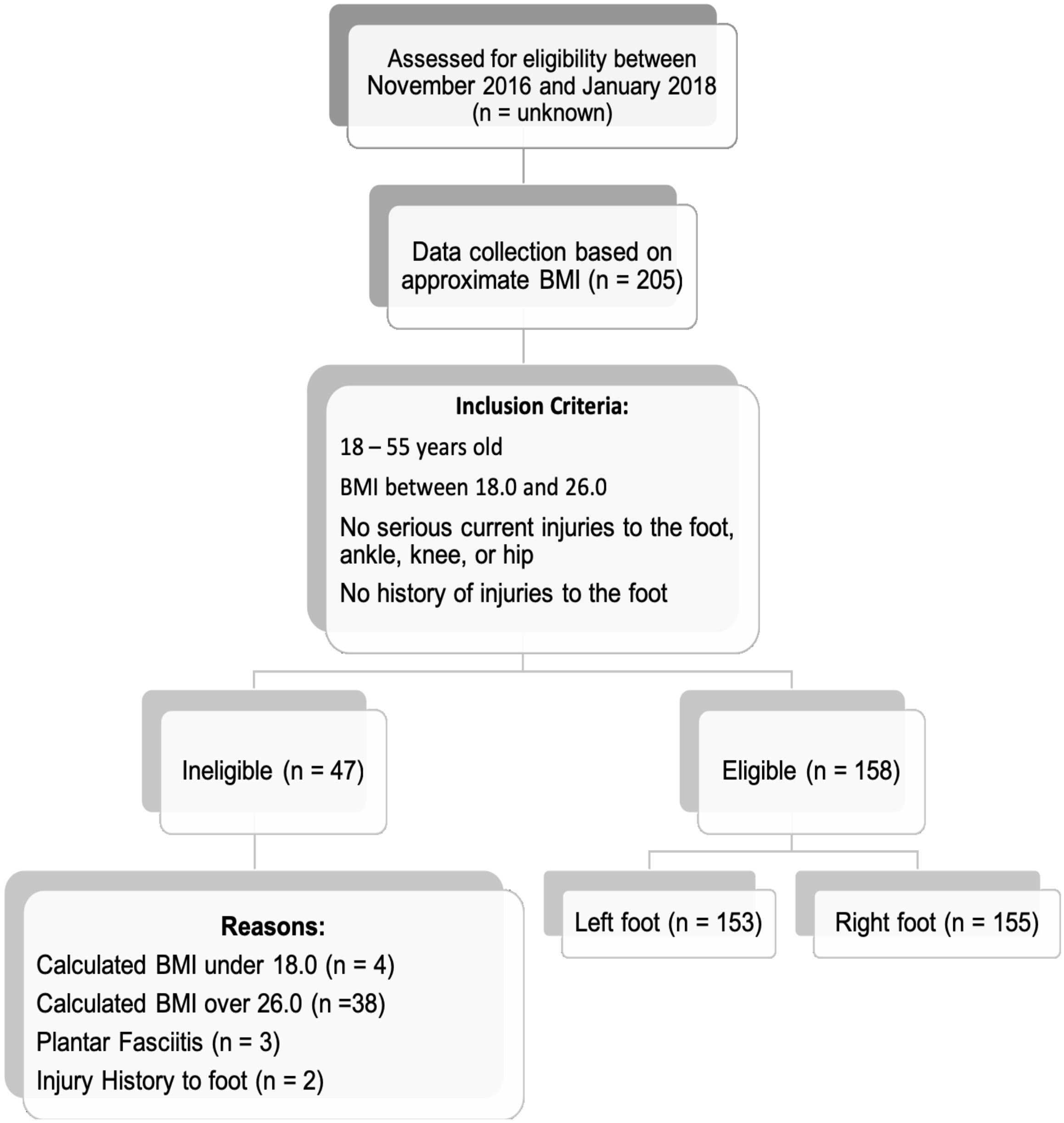


Figure 2-1: Participant flow chart

Apparatus

Participants were required to complete a basic information sheet collecting anthropometric data in order to ensure that they were eligible for participation. This study also had participants fill out a modified General Practice Physical Activity Questionnaire. This questionnaire was modified to include a section for participants to list specific types of physical activity performed. Information related to previous hard- and soft-tissue injuries to the foot and ankle joint as well as hand and foot dominance were also collected.

Ensuring that participants have suffered no major injuries that would impact their structural or functional arch types allows results to be generalized.

Figure 2-2: Image of the mirror box unit used during data collection

A mirror box unit comprised of an angled mirror placed within a wooden framed box measuring 60x30x30 cm with a 1 cm clear Plexiglas top was used during data collection, allowing the plantar surface of objects placed on top of the box to be reflected. Participants sat on an adjustable stool and placed their other foot on a height-matched box set next to the mirror box in order to ensure that the required amount of body weight was placed on the measured foot. A Nikon D5100 camera was set 1m away and 0.25 m off the ground from the box in order to capture images of the mirror and the position of the foot and leg. Camera settings were adjusted to accommodate given light levels.

Procedure

Upon completion of the information sheet, footprints of suitable participants were recorded using the mirror box unit and camera system previously described. Participants had a series of three images taken of their leg and plantar surface of each foot in the positions shown in Figure 2-3 as described below. A description of the verbal instructions is detailed in Appendix A. Once all three images were captured, the stool was moved to the opposite side of the mirror box, and the procedure was repeated on the opposite foot. Comparing the contact area of the foot in full body weight images with the unweighted image will provide a measure of functional foot arch.

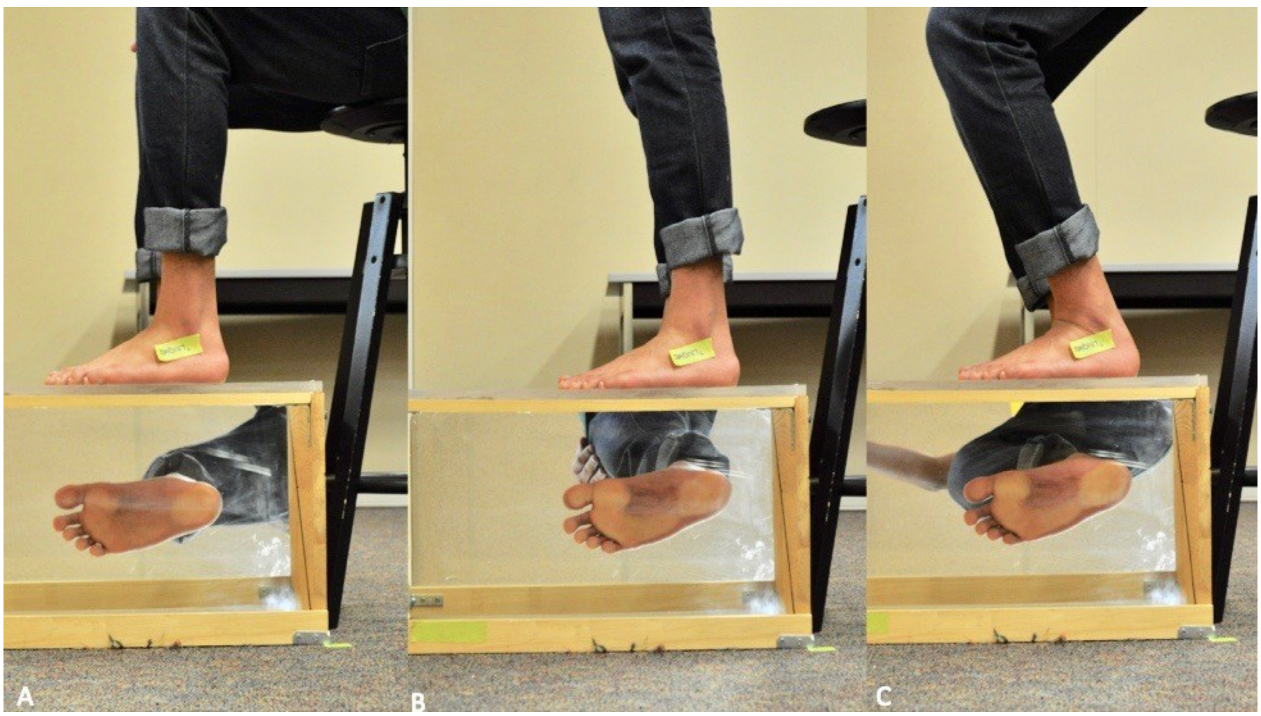


Figure 2-3: Foot and leg positions while sitting (A), standing (B), and in a partial squat position (C) during data collection

Sitting Position

Participants were instructed to place the foot of interest in the middle of the mirror box, starting at the heel and rolling their foot down in order to ensure that their entire foot made contact with the Plexiglass. Participants then placed their other foot on the adjacent box, approximately hip width distance apart, and were coached to align their leg perpendicularly to the surface of the box, creating a 90° angle at the ankle. After ensuring that they were not applying any additional downward force, the researcher documented their footprint. This first image indicates the unweighted structural arch of the foot.

Standing Position

Participants were next instructed to stand up on the two boxes and distribute their body weight equally between their two feet. Ideally the boxes were located near a wall for support, but the researcher provided assistance when required if this was not the case. Before taking the picture, the researcher ensured that the participant was standing with proper alignment.

Partial Squat Position

Participants were guided into a partial squat, squatting as deeply as possible without allowing their trunk to flex forward. Weight was to be balanced equally between the left and right feet. This position was selected to invoke maximal dorsiflexion and was held for 10 seconds before the researcher documented the image. Participants were then assisted off the mirror box.

Data Analysis

Images taken during data collection were uploaded and analyzed using a MATLAB (version 9.4, TheMathWorks, Natick, MA, USA) image software program (ArchType1.0; Edmonton, Alberta, Canada) written by the researcher to digitally analyzed the contact area of the foot and previously selected metrics (AI, AA, and Staheli and Chippaux-Smirak Indices), which have been shown to be reliable indices across trials (Papuga & Burke, 2011; Queen, Mall, Hardaker, & Muley, 2007). The footprint of an individual image was first traced, with the maximal width of the fore- and rearfoot and minimal width of the midfoot manually drawn, before the total area and the four variables were calculated. These data were then transcribed and stored in an excel document before the procedure was repeated on the remaining two images of the foot.

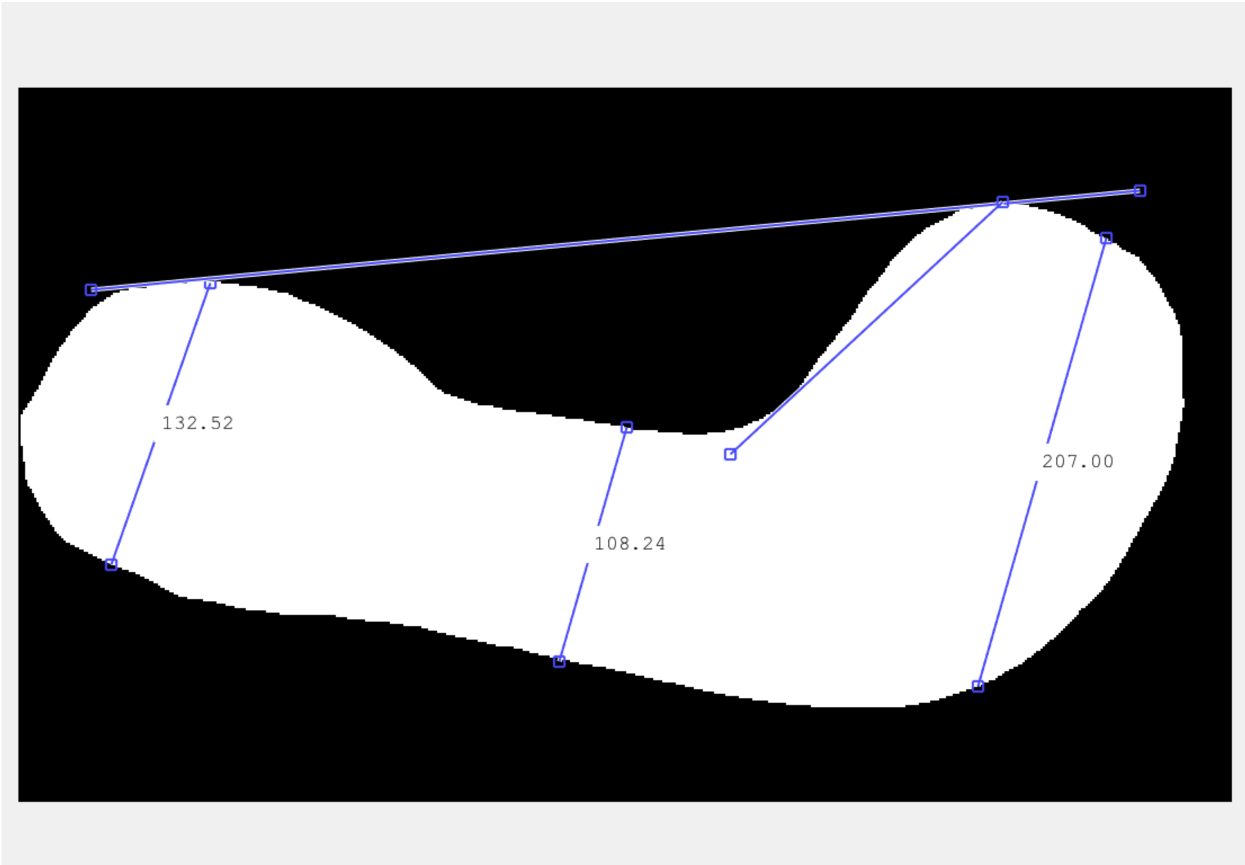


Figure 2-4: Example of footprint image in MATLAB analysis

Once each of the static images for an individual's foot were assigned a structural foot arch score, the standing and partial squat scores were compared to the sitting score to determine a functional foot arch score for the foot. Larger differences between sitting and standing scores will indicate a more flexible functional foot arch, while minimal differences between positions will represent a rigid functional foot arch.

Statistical Analysis

The primary purpose of this study was to determine the differences in structural arch characteristics between different functional foot positions. Descriptive statistics (mean and standard deviation) were used to determine structural foot arch characteristics in each position. The sitting data was then used as a baseline measure, and the difference between Standing and Sitting, and Partially Squatting and Sitting were calculated. Additionally, the mean and standard deviation of the participants' age, the changes in structural arch measures between positions using AI, and foot dominance were described. This was selected based on its application in other studies performed to establish reliability of measurement techniques (Sporndly-Nees, Dasberg, Nielsen, Boesen, & Langberg, 2011; McCrory, Young, Boulton, & Cavanagh, 1997).

Results

Descriptions

Data from one hundred and fifty-eight individuals (female: n=99; male: n=59) were used for analysis. Anthropomorphic measurements were taken for each participant as show in Table 2-1. Dominance was self-reported by participants. The average height of male participants was 1.81 ± 0.07 m and female participants was 1.67 ± 0.07 m. Body mass index was calculated to be 23.53 ± 2.01 kg/m^2 for males, and 22.16 ± 1.84 kg/m^2 for females. As the data was collectively analyzed, the average BMI of all participants was 22.67 ± 2.01 kg/m^2.

Table 2-1: Participant Characteristics

	Women (n=99)	Men (n=59)	Total (n=158)
Age (years)	23.85 ± 5.42	24.59 ± 6.65	24.13 ± 6.65
Height (m)	1.67 ± 0.07	1.81 ± 0.07	1.72 ± 0.10
Body Mass (kg)	61.64 ± 6.58	77.53 ±8.42	67.57 ±10.61
BMI (kg/m^2)	22.16 ± 1.84	23.53 ± 2.01	22.67 ± 2.01
Left Foot Dominant	4	9	13
Right Foot Dominant	95	50	145

Participants were also asked to fill out a modified General Practice Physical Activity Questionnaire to determine overall activity levels and types of exercises performed. These data are summarized in Table 2-

2. Responses from Question 2A was the most useful for this study and found that 60.5% of participants participated in 3 or more hours of physical exercise within the previous week. The most commonly listed activities were weight training, running, and circuit training.

Table 2-2: Responses for the amount of time spent on physical activity within the last week

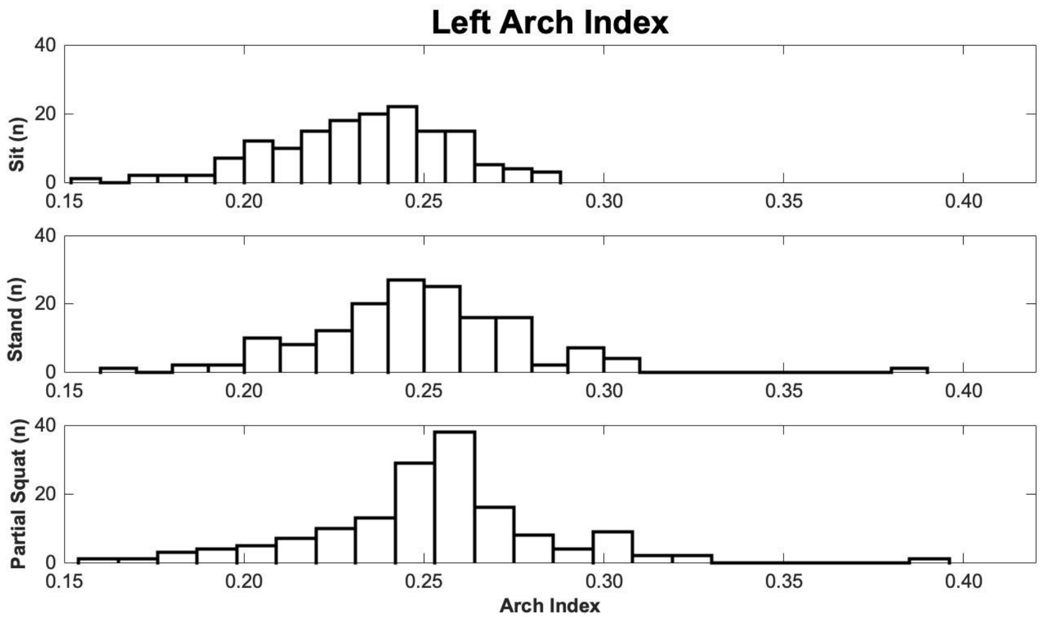
	Physical Exercises such as swimming, weight training, or aerobics	**Cycling, including to work and during leisure time**	**Walking, including to work, shopping, or for pleasure**
3 hours or more	60.5%	7.2%	59.4%
1 hour but less than 3 hours	28.0%	13.1%	27.7%
Some but less than 1 hour	4.5%	17.6%	9.7%
None	7.0%	62.1%	3.2%

Structural Arch Analysis

Arch Index, AA, Staheli and Chippaux-Smirak Indices were calculated for all images. The mean and standard deviation for these data are summarized in Table 2-3. As predicted, normal distributions were observed when analyzing structural foot characteristics in all three positions, as show in in Figures 2-5 thru 2-8.

Table 2-3: Mean and standard deviation for structural arch characteristics while participant was sitting, standing, or in a partial squat position

	Left Foot			**Right Foot**		
	Sit	**Stand**	**Partial Squat**	**Sit**	**Stand**	**Partial Squat**
Arch Index	0.23 ± 0.02	0.25 ± 0.03	0.25 ± 0.03	0.24 ± 0.03	0.25 ± 0.03	0.26 ± 0.03
Arch Angle (deg)	49.09 ± 6.23	46.74 ± 6.21	45.58 ± 7.07	48.66 ± 7.09	45.84 ± 7.68	45.05 ± 7.06
Chippaux-Smirak Index	0.42 ± 0.08	0.46 ± 0.11	0.47 ± 0.11	0.42 ± 0.09	0.46 ± 0.10	0.47 ± 0.12
Staheli Index	0.62 ± 0.12	0.68 ± 0.15	0.68 ± 0.16	0.61 ± 0.13	0.67 ± 0.16	0.68 ± 0.18



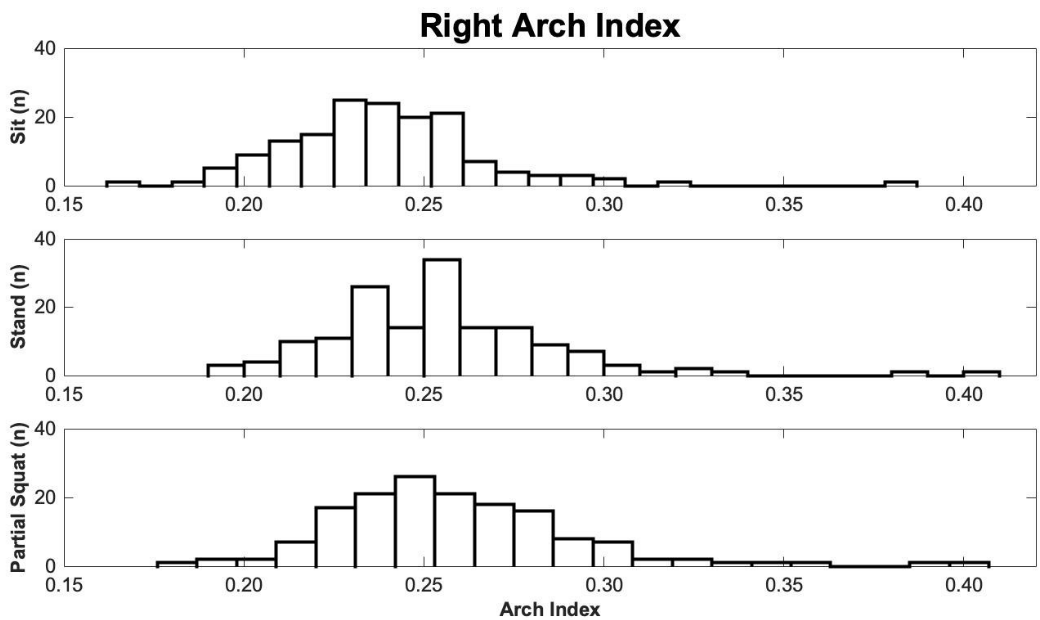


Figure 2-5: Arch Index structural arch scores of the left and right feet while the participants were in a sitting, standing, or partial squat position.

Table 2-4: Arch Index range and number of individuals with each structural arch type from sitting. Range determined from mean ± SD

		Left Foot			Right Foot		
		Pes Cavus	**Normal**	**Pes Planus**	**Pes Cavus**	**Normal**	**Pes Planus**
Arch Index	Range	0.1535 - 0.2086	0.2086– 0.2566	0.2566 – 0.2836	0.1684 – 0.2116	0.2116– 0.2660	0.2660 – 0.3831
	n	27	102	24	19	117	19
	% of total	17.65	66.67	15.69	12.26	75.48	12.26

Table 2-4 shows the range of AI scores used to classify structural arch type and was set as one standard deviation from the mean. The calculated percentages of participants in each group show that approximately normal distributions of structural foot types were found, though the right foot had a slightly higher percentage of people classified as structurally normal.

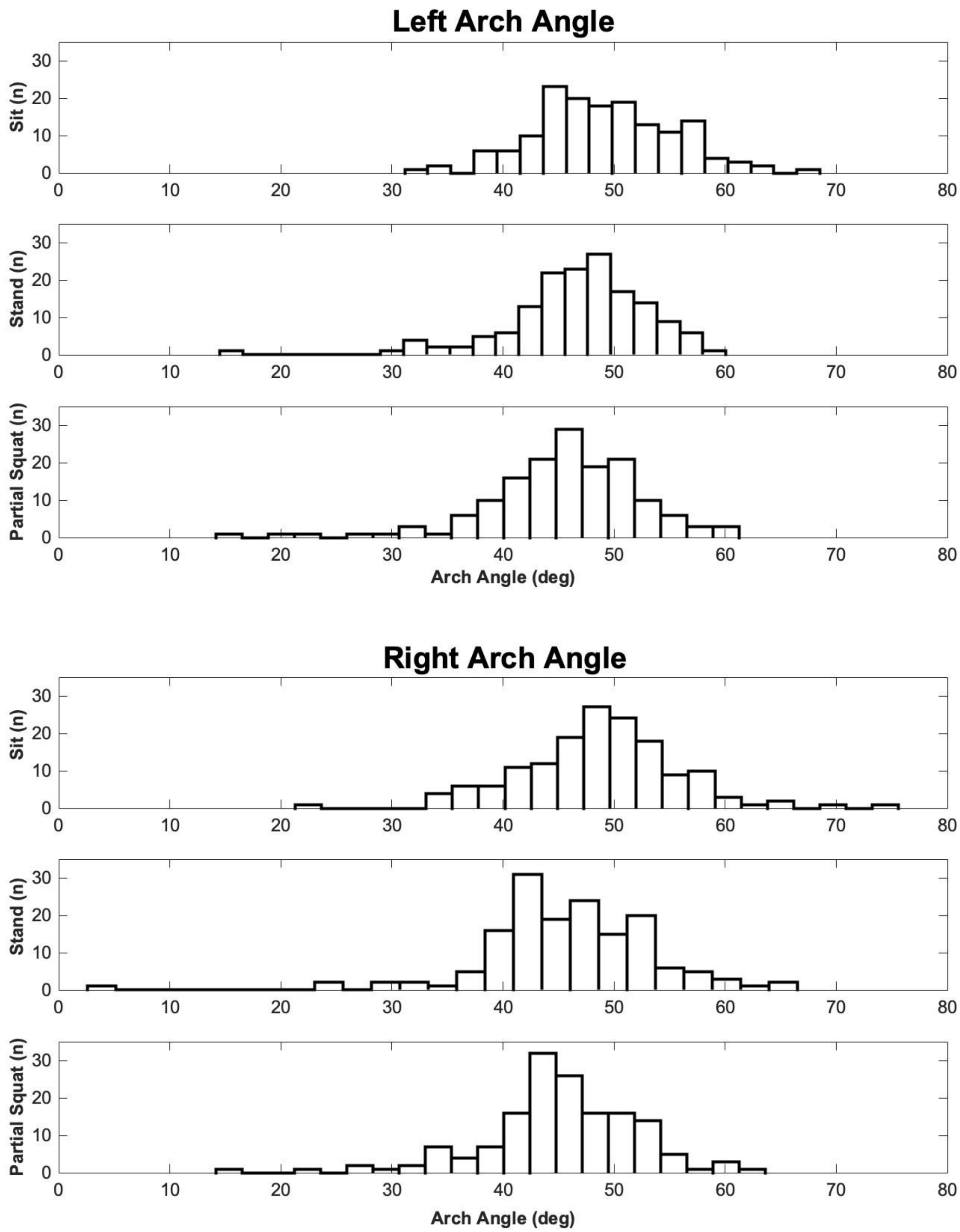


Figure 2-6: Arch Angle structural arch scores of the left and right feet while the participants were in a sitting, standing, or partial squat position.

Table 2-5: Arch Angle range and number of individuals with each structural arch type from sitting. Range determined from mean ± SD

		Left Foot			Right Foot		
		Pes Cavus	**Normal**	**Pes Planus**	**Pes Cavus**	**Normal**	**Pes Planus**
Arch Angle	Range (°)	33.0137 – 42.8608	42.8608-55.3220	55.3220 – 67.4717	21.8584 – 41.5682	41.5682-55.7435	55.7435 – 73.8645
	n	20	107	26	21	114	20
	% of total	13.07	69.93	16.99	13.55	73.55	12.90

Table 2-5 shows the range of AA scores used to classify structural arch type and was set as one standard deviation from the mean. The calculated percentages of participants in each group show that approximately normal distributions of structural foot types were found, though again, the right foot had a slightly higher percentage of people classified as structurally normal.

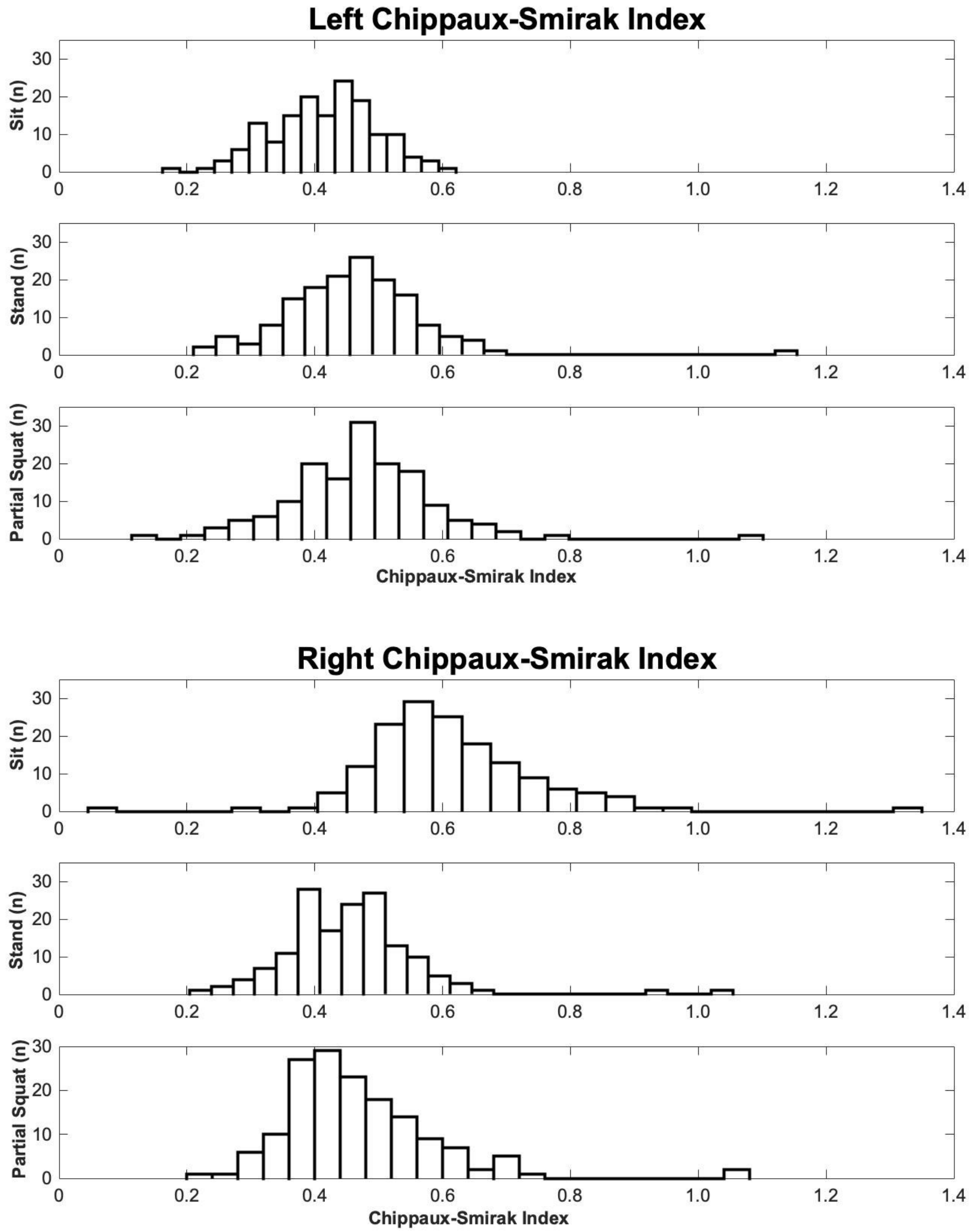


Figure 2-7: Chippaux-Smirak Index structural arch scores of the left and right feet while the participants were in a sitting, standing, or partial squat position.

Table 2-6: Chippaux-Smirak Index range and number of individuals with each structural arch type from sitting. Range determined from mean ± SD

		Left Foot			Right Foot		
		Pes Cavus	Normal	Pes Planus	Pes Cavus	Normal	Pes Planus
Chippaux-Smirak Index	Range	0.1656 – 0.3360	0.3360-0.4972	0.4972 – 0.6200	0.0757 – 0.4798	0.4798-0.7491	0.7491 – 1.3500
	n	27	101	25	15	122	18
	% of total	17.65	66.01	16.34	9.68	78.71	11.61

Table 2-6 shows the range of Chippaux-Smirak scores used to classify structural arch type and was set as one standard deviation from the mean. Though the calculated percentages of participants' left foot show an approximately normal distribution of structural foot types, the distribution is slightly less uniform than what was seen for AI and AA data. The right foot data has nearly 80% of participants classified as having a structurally normal arch type and a slightly higher occurrence of pes planus feet than pes cavus.

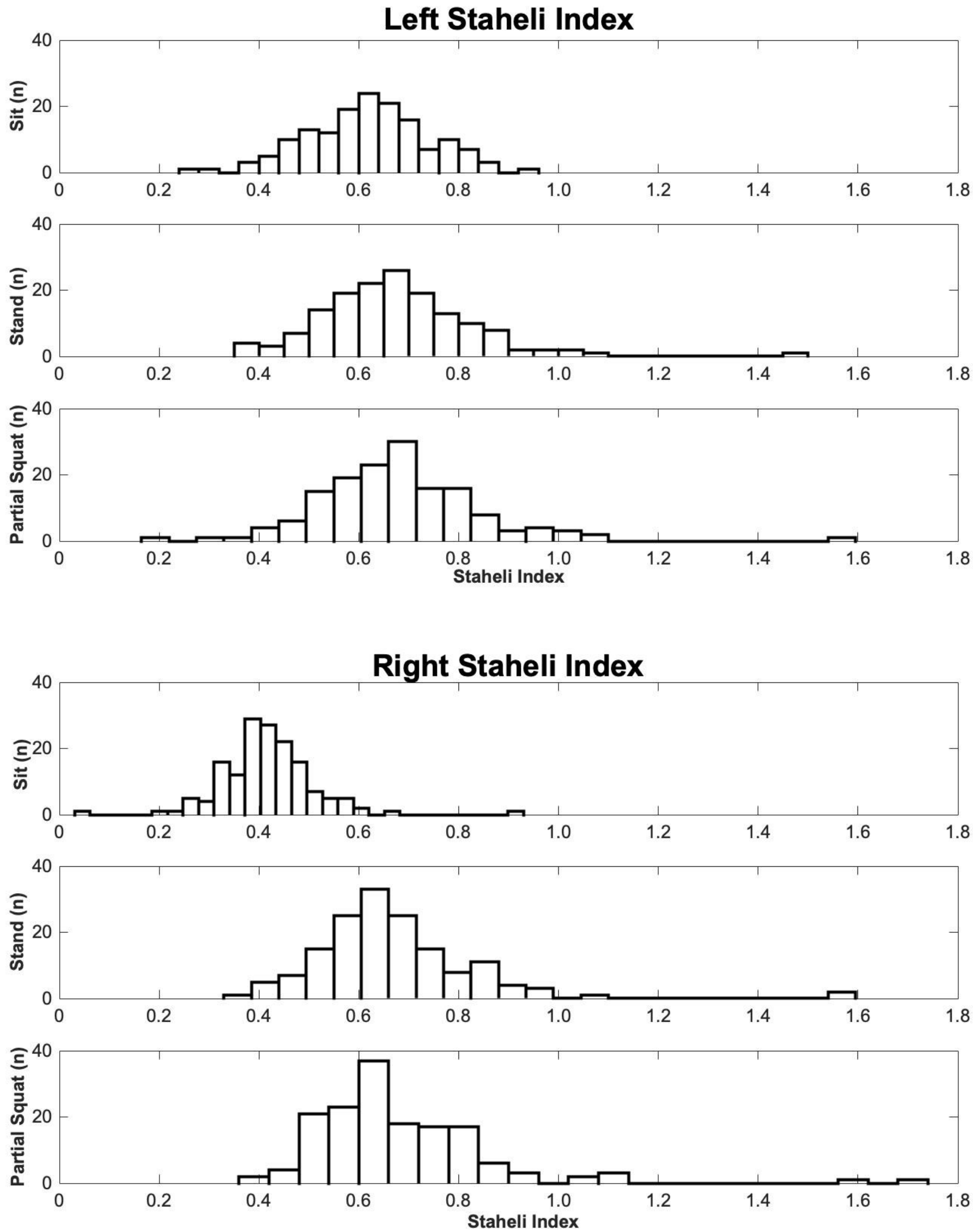


Figure 2-8: Staheli Index structural arch scores of the left and right foot while the participants were in a sitting, standing, or partial squat position.

Table 2-7: Staheli Index range and number of individuals with each structural arch type from sitting. Range determined from mean ± SD

		Left Foot			Right Foot		
		Pes Cavus	**Normal**	**Pes Planus**	**Pes Cavus**	**Normal**	**Pes Planus**
Staheli Index	Range	0.2500 – 0.4980	0.4980-0.7396	0.7396 – 0.9473	0.0554 – 0.3233	0.3233 – 0.5073	0.5073 – 0.9071
	n	27	103	23	19	120	16
	% of total	17.65	67.31	15.03	12.26	77.42	10.32

Table 2-7 shows the range of Staheli Index scores used to classify structural arch type and was set as one standard deviation from the mean. The calculated percentages of participants in each structural arch group show that approximately normal distributions of structural foot types were found for the left foot. Again, close to 80% of the right feet are classified as having a structurally normal arch type, with slightly more participants having a pes cavus structural arch type than pes planus.

Functional Arch Analysis

Arch Index was used to determine functional arch characteristics. Arch Index scores recorded when the participant was sitting were subtracted from scores recorded while the participant was in a standing or in a partial squat position providing a functional arch score. A positive change indicates that the contact area of the foot on the box surface increased when the participants were standing (Figures 2-9 and 2-10) or in the partial squat position (Figures 2-11 and 2-12) compared to when they were sitting. Functional data was initially analyzed based on the different structural arch types (Figures 2-9 and 2-11), followed by a repeat analysis grouped by left or right foot (Figures 2-10 and 2-12). Tables 2-8 and 2-11 provide the number and mean change for the left and right feet grouped by structural arch type while sitting and in a partial squat respectively. Tables 2-9 and 2-12 show the range of AI scores for each functional grouping based on structural arch type, as well as the percentage of participants in each group. Tables 2-10 and 2-13 show the range of AI scores for the functional arch types when all structural arch types were analyzed together.

Table 2-8: Change in Arch Index for different structural arch types for standing versus sitting (Mean ± SD).

	n	Left Foot	% of Total	n	Right Foot	% of Total
Pes Cavus	27	0.0262 ± 0.0213	17.65	19	0.0231 ± 0.0140	12.26
Normal	102	0.0148 ± 0.0177	66.67	117	0.0140 ± 0.0183	75.48
Pes Planus	24	0.0095 ± 0.0269	15.69	19	0.0184 ± 0.0288	12.26

Table 2-8 shows the largest mean change in AI between sitting and standing was for pes cavus foot types in both left and right feet. Pes planus arch types in left feet showed the least amount of change. The amount of change in AI in both the left and right feet for the normal arch type was approximately equivalent. These results were further analyzed in order to determine if certain functional arch types were more commonly associated with a specific structural arch type.

Table 2-9: Change in Arch Index range and number of individuals with each functional arch type when standing. Data was analyzed by structural arch type. Range determined from mean ± SD.

Difference in Arch Index (arch type)		Left Foot			Right Foot		
		Rigid	**Normal**	**Flexible**	**Rigid**	**Normal**	**Flexible**
Pes Cavus	Range	-0.0162 – 0.0048	0.0048– 0.0475	0.0475 – 0.0649	-0.0009 – 0.0091	0.0091– 0.0371	0.0371 – 0.0494
	n	6	16	5	3	13	3
	% of total	22.22	59.26	18.52	15.79	68.42	15.79
Normal	Range	-0.0409 – -0.0029	-0.0029– 0.0324	0.0324 – 0.0584	-0.0322 – -0.0043	-0.0043– 0.0323	0.0323 – 0.0550
	n	13	75	14	15	83	19
	% of total	12.75	73.53	13.73	12.82	70.94	16.24
Pes Planus	Range	-0.0298 – -0.0174	-0.0174 – 0.0364	0.0364 – 0.1038	-0.0147 – -0.0103	-0.0103 – 0.0472	0.0472 – 0.1150
	n	4	18	2	2	16	1
	% of total	16.67	75.00	8.33	10.53	84.21	5.26

Table 2-9 shows the range of functional arch types in each structural foot type while moving from sitting to standing. Nearly all the individuals with a rigid functional arch type recorded a negative change between positions, indicating that the ratio of the area of the middle third of the footprint relative to the total area decreased in a standing position. Figure 2-9 and Table 2-9 indicate normal distributions for functional arch types in the structurally normal foot. This relationship is also suggested in the other functional types as well by the breakdown of percentages of total feet, though both the pes cavus and planus groups were underpowered. Excluding the outlier in both the left and right pes planus foot (Figure 2-9), the observed functional range is consistent between structural arch types, so the analysis was repeated grouping structural arch types together.

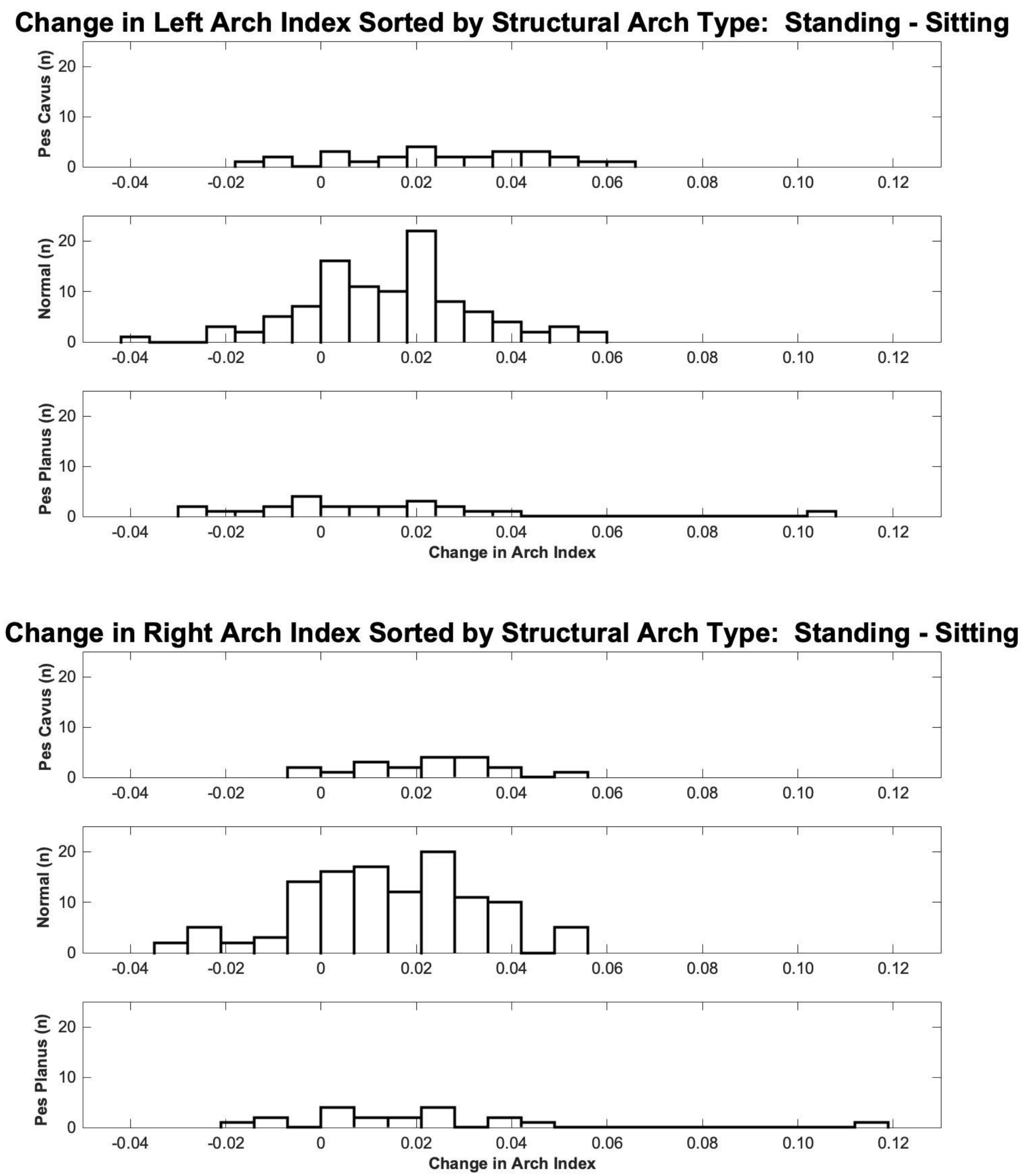


Figure 2-9: Difference in structural arch scores between the standing and sitting positions. Foot types were initially sorted based on unweighted structural Arch Index scores.

Means and standard deviations of the data show that few data points lie outside of one standard deviation and a normal distribution is observed for functional arch scores for both feet with a normal structural arch score. Though the sample size is smaller, pes cavus feet also show an approximate normal distribution in functional arch scores while standing, with slightly more flattening than those with a normal foot type. There is an observable outlier with a greater than expected amount of flattening in the planus functional arch scores while sitting in both the left and right feet. Overall however, planus functional arch scores while sitting show flattening, but to a lesser degree than cavus or normal feet.

Table 2-10: Change in Arch Index range and number of individuals with each functional arch type when standing. Structural arch types were analyzed collectively. Range determined from mean ± SD

		Left Foot			Right Foot		
		Rigid	**Normal**	**Flexible**	**Rigid**	**Normal**	**Flexible**
Difference in Arch Index	Mean ± SD	-0.0145 ± 0.0089	0.0150 ±0.0109	0.0501 ± 0.0144	-0.0159 ± 0.0079	0.0150 ± 0.0110	0.0466 ± 0.0168
	Range	-0.0409 – -0.0045	-0.0045– 0.0365	0.0365 – 0.1038	-0.0322 – -0.0039	-0.0039– 0.0352	0.0352 – 0.1150
	n	21	110	22	18	116	21
	% of total	13.37	71.90	14.38	11.61	74.84	13.55

Table 2-10 shows the range of the change in AI scores as participants moved from a sitting to standing position used to classify functional arch type when structural arch types were grouped together. Range was set as one standard deviation from the mean. The calculated percentages in each group show that approximately 70-75% of participants' change in structural AI scores from sitting to standing was within the normal functional range. This is reinforced when looking at the distribution of functional arch scores in Figure 2-10, again ignoring the previously mentioned outlier in both the left and right foot. As with the structural arch type, the right foot had a slightly higher percentage of people fall in the normal functional arch range when moving from a sitting position to a standing one.

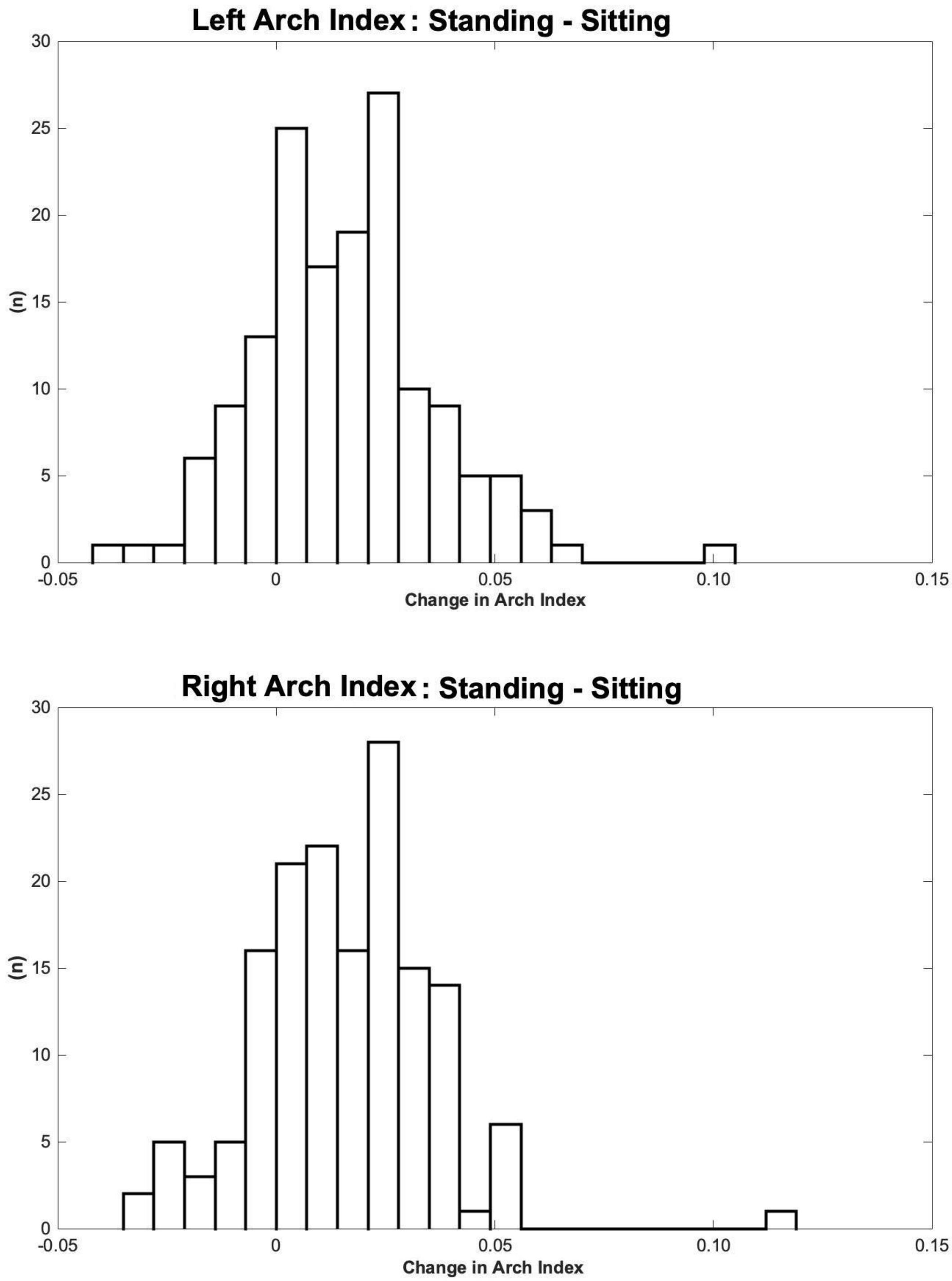


Figure 2-10: Difference in structural Arch Index scores between the standing and sitting positions. Foot types were analyzed together.

Table 2-11: Change in AI for different structural arch types for partial squat versus sitting (Mean ± SD).

	n	Left Foot	% of Total	n	Right Foot	% of Total
Pes Cavus	27	0.0239 ± 0.0238	17.65	19	0.0260 ± 0.0199	12.26
Normal	102	0.0189 ± 0.0213	66.67	117	0.0176 ± 0.0200	75.48
Pes Planus	24	0.0147 ± 0.0281	15.69	19	0.0292 ± 0.0341	12.26

Table 2-11 shows the largest mean change in AI between a partial squat and sitting was in the right feet of pes planus foot types, but interestingly, the left pes planus feet showed the least amount of change. The next largest mean difference observed in the left and right pes cavus arch types. The amount of change in AI for the normal foot type was slightly larger in the left feet than the right.

Table 2-12: Change in Arch Index range and number of individuals with each functional arch type when partially squatting. Data was analyzed by structural arch type. Range determined from mean ± SD.

Difference in Arch Index (arch type)		Left Foot			Right Foot		
		Rigid	Normal	Flexible	Rigid	Normal	Flexible
Pes Cavus	Range	-0.0157 – 0.0001	0.0001– 0.0477	0.0477 – 0.0717	-0.0098 – 0.0061	0.0061– 0.0459	0.0459 – 0.0684
	n	4	17	6	2	14	3
	% of total	14.81	62.96	22.22	10.53	73.68	15.79
Normal	Range	-0.0502 – -0.0023	-0.0023– 0.0402	0.0402 – 0.0944	-0.0226 – -0.0024	-0.0024– 0.0376	0.0376 – 0.1069
	n	11	80	11	18	83	16
	% of total	10.78	78.43	10.78	15.83	70.94	13.68
Pes Planus	Range	-0.0283 – -0.0134	-0.0134 0.0428	0.0428 – 0.1038	-0.0207 – -0.0048	-0.0048 – 0.0633	0.0633 – 0.1242
	n	3	19	2	1	16	2
	% of total	16.67	79.17	8.33	5.26	84.21	10.53

Table 2-12 shows the range of functional arch types in each structural foot type comparing sitting AI scores to AI scores recorded in a partial squat. A normal distribution is again observed in functional foot scores for both feet, but there is a larger range in scores when compared to the standing functional arch scores for normal feet. As found in the standing functional scores, the range in functional scores was similar regardless of structural arch type (Figure 2-11), though was slightly larger compared to the functional standing range. Cavus functional foot scores show that flattening occurs for most of the participants, again to a larger degree than those with normal structural arch types. It is likely that the left foot data contains an outlier for cavus foot types showing an unexpected amount of flattening, as well as in both the left and right planus foot types. If the outliers are ignored, planus functional arch scores indicated that less MLA flattening is observed compared when compared to normal and cavus arch types.

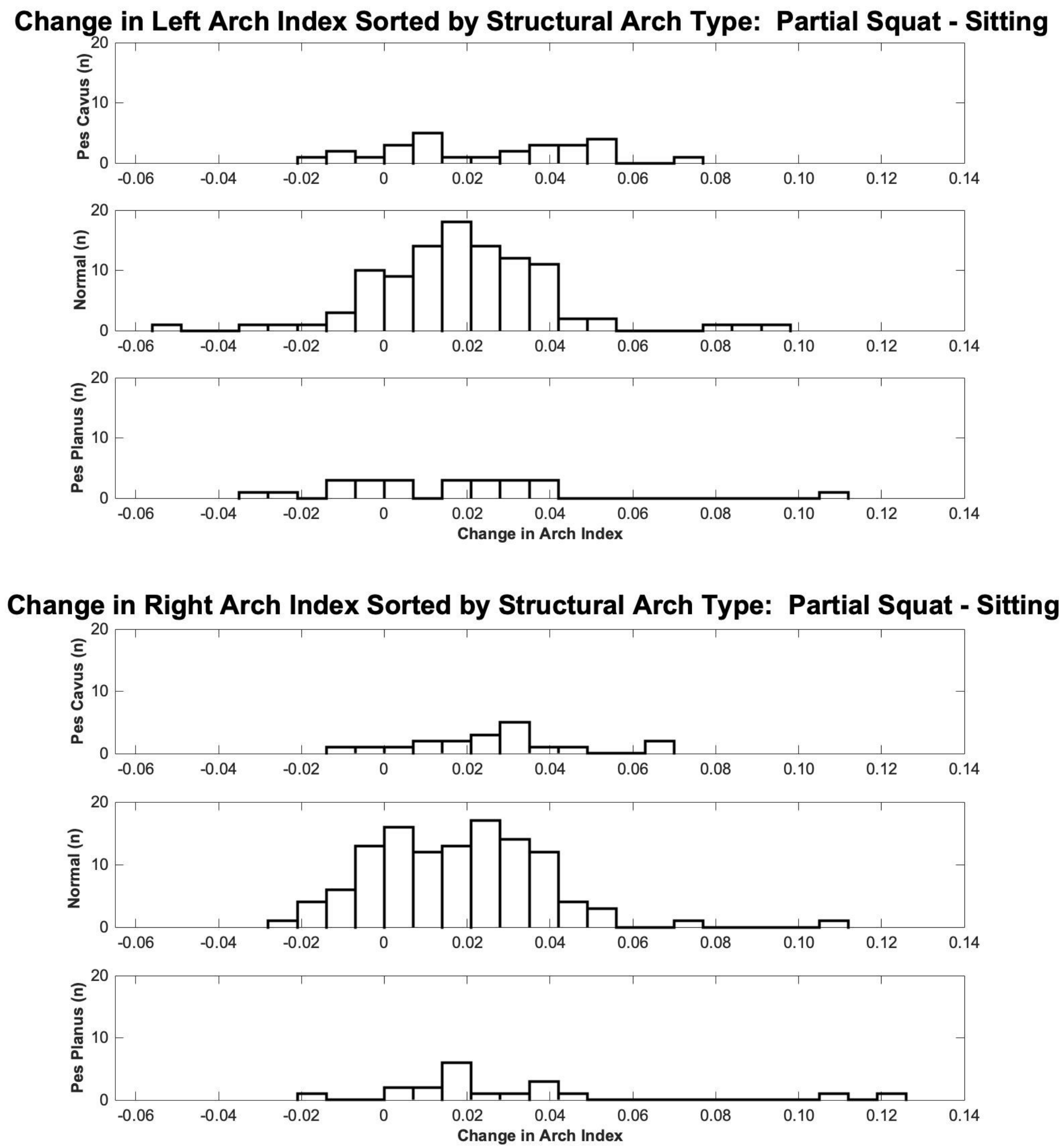


Figure 2-11: Difference in structural arch scores between the partial squat and sitting positions. Foot types were initially sorted based on unweighted structural Arch Index scores.

Table 2-13: Change in Arch Index range and number of individuals with each functional arch type when partially squatting. Range determined from mean ± SD.

		Left Foot			Right Foot		
		Rigid	**Normal**	**Flexible**	**Rigid**	**Normal**	**Flexible**
Difference in Arch Index	Mean ± SD	-0.0144 ± 0.0119	0.0197 ± 0.0123	0.0613 ± 0.0204	-0.0090 ± 0.0068	0.0198 ± 0.0115	0.0595 ± 0.0241
	Range	-0.0502 – -0.0037	-0.0037– 0.0420	0.0420 – 0.1083	-0.0226 – -0.0019	-0.0019– 0.0408	0.0408 – 0.1242
	n	22	115	16	23	116	16
	% of total	14.38	75.16	10.46	14.84	74.84	10.32

Table 2-13 shows the range of change in AI scores used to classify functional arch type as the participant moved from a partial squat to standing position. Range was set as one standard deviation from the mean. The calculated percentages in each group show that the majority of participants' change in structural AI scores was within the normal range, and the number that did not fall in this range were balanced on either end of normal. As with the structural arch type, the right foot had a slightly higher percentage of people fall in the normal functional arch range when moving from a sitting position to a standing one. Outliers are observable in both the left and right feet indicating a larger than expected structural arch change in two participants in the right foot, and at least one in the left foot.

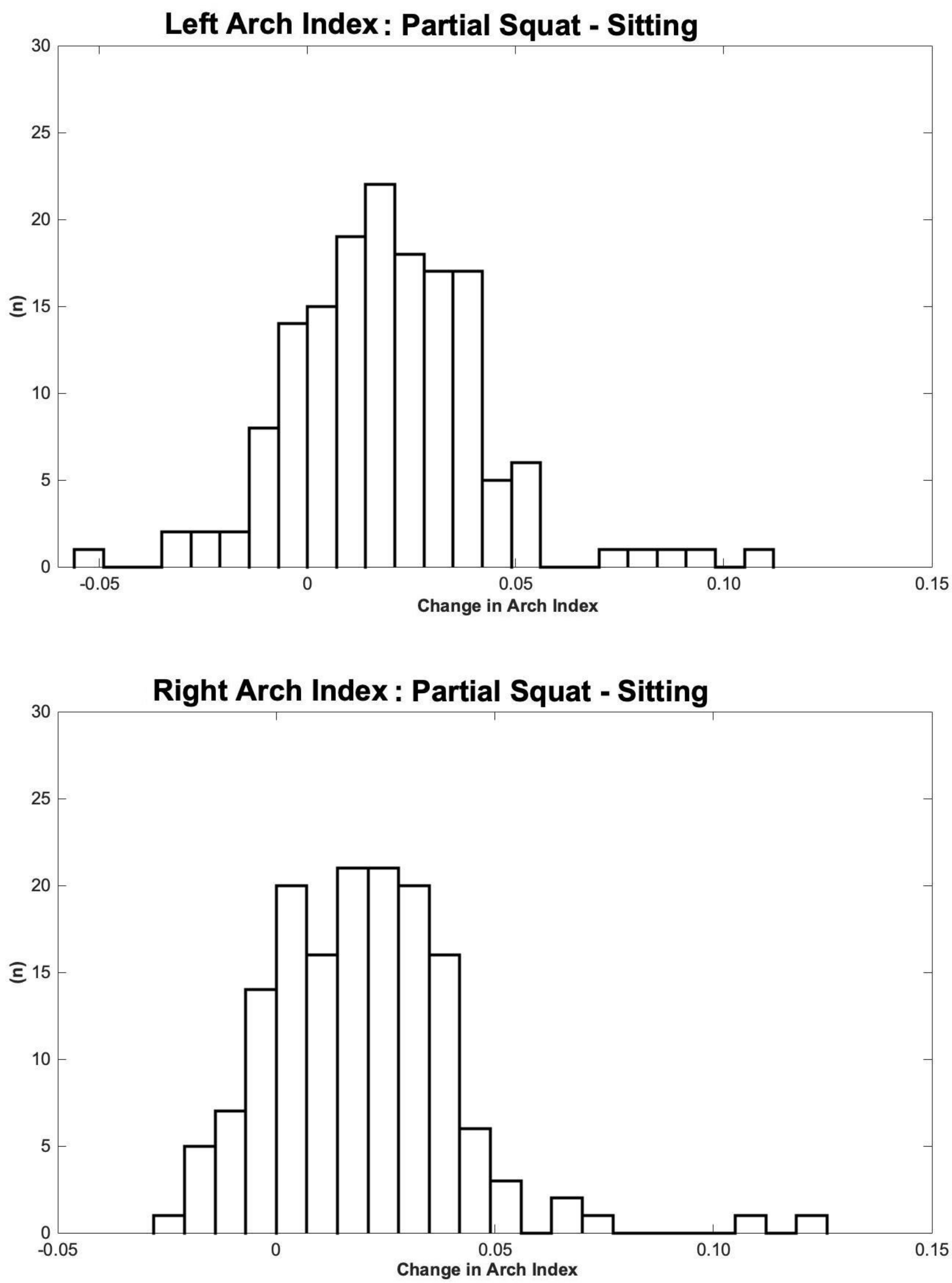


Figure 2-12: Difference in structural Arch Index scores between the partial squat and sitting positions. Foot types were analyzed together.

Discussion

Structural Arch Characteristics

The aim of this study was to establish a classification system that provides both structural and functional arch characteristics. We hypothesized that measuring structural arch footprints under different loading conditions would showcase the functional range of the MLA. For the purposes of this paper, structural arch types reflect scores calculated while in the sitting (unweighted) position and are considered the baseline measure unless otherwise stated. Results indicate that there is a standard range of MLA deformation, regardless of the structural foot type.

This study calculated structural arch scores using four of the commonly used metrics: AI, AA, and Chippaux-Smirak and Staheli indices. Images were recorded while participants were in three different positions that were selected to progressively invoke calcaneal plantar flexion and decrease the height of the MLA (Chizewski & Chiu, 2012). As show in Figures 2-5 through 2-8, normal distributions were observed in both left and right feet for all calculated metrics in each of the three positions. This was the first step in establishing that the field tool and analysis method functioned as anticipated.

When compared to previous research, the mean structural arch scores recorded in the sitting position fell within the expected range for all variables except the Chippaux-Smirak Index (Table 2-3), which was lower than expected with a mean score of 0.42 in both the left and right feet (Cavanagh & Rogers, 1987; Clarke, 1933; Queen, Mall, Hardaker, & Muley, 2007). It should however be noted, that Staheli Index scores fell in the lower range of a reported structurally normal arch (mean L/R: 0.62/0.61), and AA scores were on the upper range (mean L/R: 49.09º/48.66º). Possible reasons for Chippaux-Smirak scores deviating from previous research are discussed below. Mean AI scores increased slightly for both feet while participants were in the standing position (L/R: 0.25/0.25) and partial squat position (L/R: 0.25/0.26) but were still in the predicted range (Table 2-3). Arch Angle values also slightly changed based on position; 46.74º and 45.84º were observed in the left and right feet respectively while standing, and 45.58º and 45.05º while in the partial squat. As with the sitting structural arch scores, Staheli Index scores while standing and in a partial squat fell on the lower end of the expected range, (mean L/R: 0.68/0.67 standing; mean L/R: 0.68/0.68 partial squat). Chippaux-Smirak Index scores fell outside of expected values in all positions (mean L/R: 0.46/0.46 standing; mean L/R: 0.47/0.47 partial squat).

Though Chippaux-Smirak Index scores have consistently been viewed as a reliable method of determining structural arch type, data from this study consistently fell outside of the predicted normal range (Mathieson, Upton, & Birchenough, 1999; Queen, Mall, Hardaker, & Muley, 2007). The normal curve for these data is negatively skewed when compared to previous research. This could be due to an error in analysis from the researcher either finding the midfoot width to be too narrow, the forefoot width to be too wide, or a combination of the two. However, early reanalysis done in order to establish intra-rater reliability indicates consistency with previous results. An alternative possibility could be that Chippaux-Smirak Index may not actually be an appropriate method of determining structural arch type.

The Chippaux-Smirak Index looks at the ratio of the narrowest part of the midfoot compared to the widest part of the forefoot, with smaller scores indicating a higher structural arch. Research examining the evolutionary form and function of the forefoot has shown evidence that the wider forefoot is part of bipedal evolution that distinguishes humans from chimpanzees (Fernández, et al., 2018; Fernández, Holowka, Demes, & Jungers, 2016). The broad mediolateral metatarsal heads differ significantly than those found in chimpanzees, which creates increased articulating surfaces for the proximal phalangeal bases to slide against. This serves two functions, the first being to increase stability of the forefoot when experiencing peak loads, such as during terminal stance in the gait cycle. The second function is to increase dorsiflexion at the metatarsal phalangeal joints, thus activating the Windlass mechanism to increase MLA height and overall stability in the foot. This is supported by research by Matsushita *et al*. (2018) examining transverse longitudinal arch function during gait. It is therefore reasonable to question whether the forefoot width should be used to predict structural MLA characteristics as it does when using the Chippaux-Smirak Index.

Standardization of Techniques

This research demonstrated the ability for static measurement techniques to record MLA changes based on the position data was captured it. This reinforces the need for a standardized protocol for recording foot characteristics in order for future research to be comparable. Previous to this work, Cavanaugh (1987) measured AI in a standing, static position with weight equally distributed between the feet, Queen *et* al. (2015) recorded in a standing 90% weight bearing stance, Wearing *et al.* (2012) used a dynamic "first step" protocol, and Wong *et al.* (2012) did not specify the body position data was recorded in. Despite this variance, results and ranges have historically been considered comparable.

A true baseline measurement should be recorded while the participant is sitting, with the leg perpendicular to the ground and weight evenly distributed between the feet, ensuring the arch is in an unweighted position. As space can sometimes be limited when using dynamic mythologies, a secondary standing baseline position should also be set with the participant standing in a 50% weightbearing stance (Cavanagh & Rogers, 1987). Reliability and validity comparisons are therefore only appropriate based on how the data was collected.

Additionallly, an updated version of the MATLAB program will need to be created for use in future analysis. Because the current version of the program used for this thesis relied upon the researcher tracing the footprint and manually drawing in the footprint widths the Staheli and Chippaux-Smirak indices rely upon, possible sources of error were introduced. While the manual tracing of footprints produced accurate data, footprint images were not precisely aligned with the width of the mirror box and therefore data used in this thesis had a higher degree of subjectivity. The future iteration of the program will need to ensure that participants feet are aligned with the longitudinal axis of the mirror box during future data collection.

Functional Arch Characteristics

Arch Index was selected to determine functional characteristics; this metric is commonly used in research with high reliability, and baseline structural data most closely aligned with previous research. Determining functional arch type in addition to structural arch type provides a more complete picture of the foot and allows practitioners to better provide treatment or training tailored to individual need. This methodology was designed to challenge the assumption that MLA deformation does not occur in pes cavus feet or that it occurs excessively in pes cavus feet. It was hypothesized that observable MLA deformation would occur, as evidenced by changing structural arch scores, and that just as there are a range of structural arch types, a range of functional arch types would be observed within each of the three structural arch types. Following this methodology ensures that foot types on the extreme ends of the spectrum are properly classified, and that data is comparable between studies going forward.

As predicted, a range of differences in AI scores existed when comparing unweighted baseline sitting scores to scores in weighted positions. Positive changes signify increased AI in weighted positions compared to the unweighted baseline, indicating a flattening of the MLA. Data was initially sorted and analyzed based on structural arch type, as functional characteristics are commonly attributed to specific structural arch types (Okita, Meyers, Challis, & Sharkey, 2013). The upper and lower boundary for rigid and flexible functional arch types was set as one standard deviation from the mean respectively. The analysis showed a similar range of change experienced when comparing sitting scores to both standing and partial squat scores (Figures 2-9 and 2-11). Regardless of the structural arch type, the majority of footprints analyzed fell between -0.02 and 0.05 while standing, and -0.03 and 0.06 in a partial squat in both left and right feet (Tables 2-9 and 2-12). This differs from the expectation that functional scores would skew negatively for pes cavus feet (indicating minimal change in arch height), and pes planus scores would skew positively. Because participants were not recruited based on their structural arch type, pes cavus and pes planus foot types were under-powered in secondary analysis, which prevented strong conclusions from being drawn.

Overlapping ranges between of AI scores between structural and functional arch types reinforce a lack of correlation and inability to determine overall foot function from structural arch characteristics alone. Though minimal research has been done investigating the direct relationship between structural and functional arch characteristics, calcaneal plantar flexion has been documented during the midstance phase of gait and while performing a partial squat, suggesting that these positions elicit MLA deformation (Stamm & Chiu, 2015; Chizewski & Chiu, 2012). Medial longitudinal arch flattening therefore likely occurs due to a “reverse” Windlass mechanism, where the plantar aponeurosis tightens due to calcaneal plantar flexion in combination with the metatarsal phalangeal joint remaining either fixed in neutral, or in a plantar flexed position. The slightly positive skew of pes cavus feet suggests that more deformation is possible compared to the normal structural arch, while the slightly negative skew of pes planus feet aligns with there being physically less room for the MLA to deform. More positive outliers were observed in pes planus feet compared to the other structural arch types, suggesting that perhaps a hyper-flexible pes planus foot type exists. It was also interesting to observe minor mean differences between the left and right feet, with the right foot recording a smaller mean value in all functional foot types in both weighted positions. 91.8% of participants recorded right foot dominance, which makes it possible that the plantar soft tissues are stronger or contribute to increase the overall stiffness of the foot.

Due to the overlapping ranges, functional data was reanalyzed collectively; boundaries for rigid and flexible groups again were set as one standard deviation of the mean. Figures 2-10 and 2-12 show approximately normal distributions for AI changes between the standing and sitting, and partial squat and sitting positions respectively. Overall, 110 individuals had functionally normal left arch types (72% of participants) and 116 individuals had functionally normal right arch types (75% of participants) in the standing position (Table 2-10). Mean AI differences while standing was 0.0150 $\pm$ 0.0109, and 0.0150 $\pm$ 0.0110 for the left and right feet respectively. Rigid functional arch types had 21 left and 18 right feet (13% L/14% R), while 22 left (11%) and 21 right (13%) feet were classified as functionally flexible. As with the previous analysis, an outlier was noted around 0.10 and 0.12 in the left and right feet (Figure 2-10), which indicates a 137% increase in surface area between the sitting and standing positions. Possible explanations for this include an error in data collection or analysis, or that this individual falls into a separate hyper-flexible functional arch type. As a similar outlier was noted in Figure 2-12 in the partial squat position, this seems to suggest the later. An example of a potential hyper-flexible functional arch type is shown Figure 2-13. Almost the entirety of the footprint is in contact with the mirror box surface while standing, demonstrating an extreme pes planus structural arch type in a weighted position. Because participants with BMIs exceeding 26.0 and previous injuries to the foot were excluded, we can be confident that though uncommon, this foot type exists in the general population.

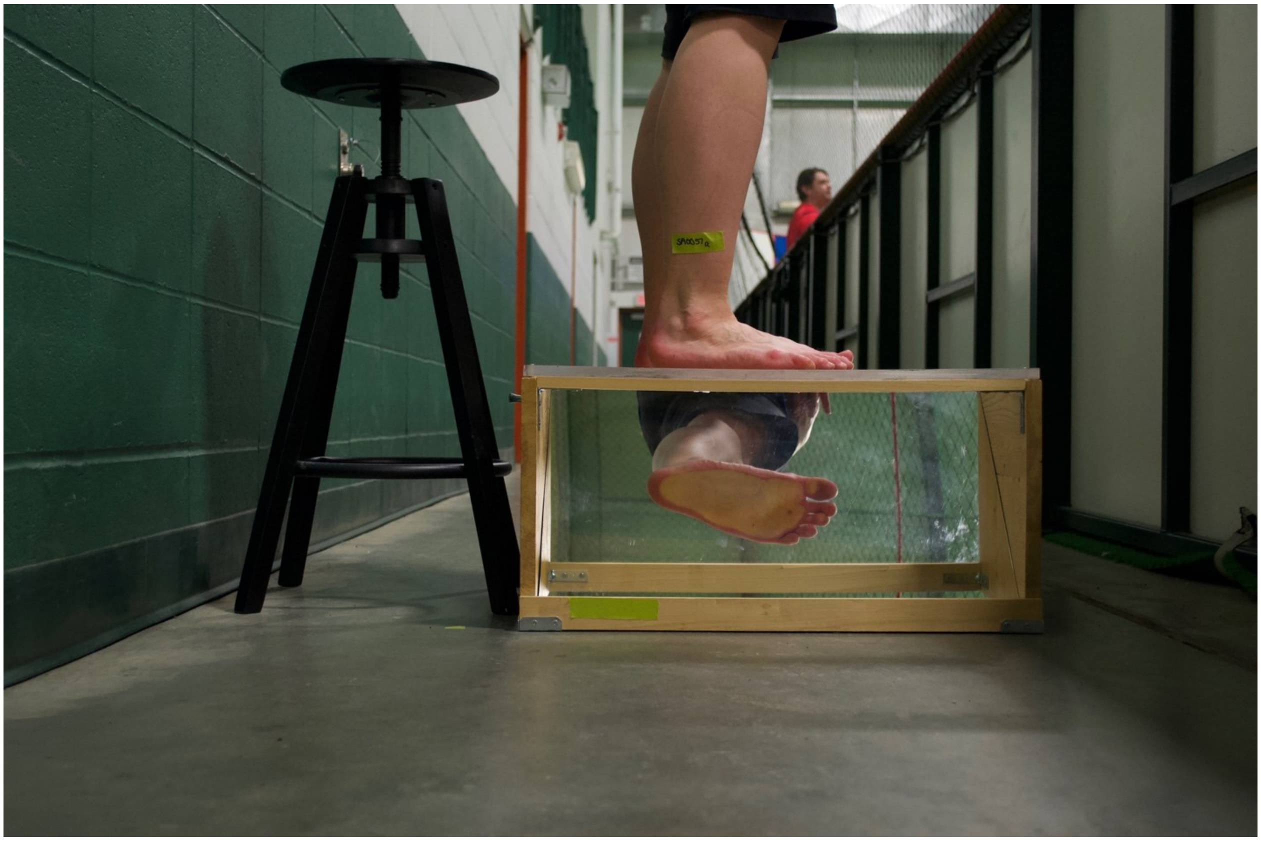


Figure 2-13: Example of a hyper-flexible pes planus foot type with excessive MLA flattening

In the partial squat position, 115 individuals had functionally normal left arch types and 116 functionally normal right arch types with mean AI changes of 0.0197 $\pm$ 0.0123, and 0.0198 $\pm$ 0.0115 respectively (Table 2-13). Approximately 75% of participants had functionally normal arch types for both left and right feet. In left feet, approximately 14% of participants (n = 22) had functionally rigid arch types compared to 15% in right feet (n =23), and approximately 10% of participants had functionally flexibly arch types in both left and right feet (n = 16L/16R). Though an attempt was made to collect data on an average population, it is very likely that both rigid and flexible functional arch types are not proportionately represented as both pes cavus and pes planus structural arches were also under represented. When looking at AI changes in the partial squat position, it is interesting to note a slight increase in potential outliers compared to the change when standing, particularly in left feet (Figure 2-12). As this position was selected to potentially elicit increased flattening of the MLA, the apparent increase in outliers could be because more participants had significantly decreased arch heights in response to the position, or it is possible that there were errors in data collection or analysis. These errors in data collection specifically refer to the position of the gaze during the partial squat position and how the direction of focus can impact balance strategies an individual employs, as the position of the centre of pressure in the foot will impact MLA height (Neumann, 2013). Because the maximal and minimal widths in the fore- mid- and rearfoot were manually selected during analysis, it is also possible that errors were derived here. Further research will need to be conducted before firm conclusions can be drawn. As structural arch type appears not to influence functional arch type, it will be important for future studies to have strictly defined methodologies in order for results to be comparable. Though the initial premise that structural arch types had a linked functional arch type appears to be incorrect, functional arch data still supports the hypothesis that structural arch data cannot be relied upon to qualify functional arch type.

Physical Activity Characteristics

Participants were instructed to complete a modified General Purpose Physical Activity Questionnaire to gauge physical activity levels and patterns. The primary questions of interest asked participants to quantify the number of hours spent a) on physical exercise or b) cycling. 64.3% of respondents were classified as 'Active' and 23.6% were classified as 'Moderately Active' (2013). 58.9% of respondents specified at least one type of exercise; activities performed varied broadly and included ice hockey, dance, rock climbing, and yoga. Though self-reported physical activity responses typically over-estimate activity levels, these data still suggest that a significant portion of participants maintain active lifestyles. These data can be looked at in the future to examine if active individuals are more likely to have a normal functional arch type due to increased strength and regulation in supporting plantar musculature (Kelly, Cresswell, Racinais, Whiteley, & Lichtwark, 2014; Kelly, Kuitunen, Racinais, & Cresswell, 2012). Further breakdown of the data linking participants with their complete foot type characteristics and specific exercise choices could examine if a relationship exists between foot types and the types biomechanical activity patterns performed.

Footwear

The effect footwear is having on the forefoot due to toe box shape is another important consideration. Until relatively recently, the shoe functioned primarily as a physical barrier to protect the foot from the environment, and therefore has a simplistic design (Goonetilleke R. S., 2013). With changes in fashion and access to a wider variety of materials and manufacturing techniques, the toe box has become significantly narrower in modern footwear. Medial longitudinal arch structure and function impairment may result from chronic interruption of forefoot regulation of the Windlass mechanism and joint pathologies, in addition to the alteration of gait mechanics resulting from reduced rearfoot motion. The forefoot has also been identified as the most common location of pain if footwear was listed as the primary cause (Branthwaite, Chockalingam, & Greenhalgh, 2013). Decreased toe box width and volume may result in a variety of foot pathologies and deformities occurring over time, especially if ill-fitting shoes are worn while the foot is still developing (Branthwaite, Chockalingam, & Greenhalgh, 2013; Bosch, Gerb, & Rosenbaum, 2010).

It will also be interesting to see the effects Nike's new ZoomX Vaporfly Next% elite running shoes will have on the MLA. Released in 2019, Nike has boasted the ability to make users of this shoe over 4% more efficient in long distance events, exceeding the ability of the Vaporfly's released in 2016 (Gonzales 2019, Gonzales 2017) Historically, elite marathon runners utilize a forefoot or midfoot striking pattern, making use of the elastic components in Windlass mechanism in the MLA, and Achilles tendon in the calf to efficiently translate energy within the kinetic chain. With the Next% shoe, Eliud Kipchoge was able to come within 25 seconds of breaking the 2-hour mark in an optimized marathon race. In a Nike-funded study comparing the Vaporfly to Nike Zoom Streak 6's and Adidas Adios Boost 2 shoes, it was determined that due to the unique springy foam (Pebax) and carbon firbre midplate used in the midsoles of the shoe, 87% of the impact energy was able to be returned to the runner in the Vaporfly, compared to 76% and 66% in the Boost 2 and Streak 6 respectively in lab conditions, regardless of the runners strike pattern (Barnes & Kilding, 2019). The exact mechanics of the energy-saving properties are unknown, yet largely thought to come from the foam, which is described as feeling "squishy and springy". An improvement has already been observed between the Next% (2019) and Vaporflys (2017). The midplate is thought to have a minor contribution and helps to stabilize the runner's ankle and align the toes to limit flexion within the shoe, however, without future experiments testing the Pebax and midplate in isolation, the true effects of the technological components remain unknown. How this will ultimately affect the MLA is yet to be seen, however, restricting dorsiflexion in the toes will likely decrease the efficiency of the MLA, which could result in weaker plantar intrinsic muscles and contribute to described foot pain in the future.

Experimental Conditions and Limitations

A major limitation of this study was that participants were likely not representative of the general population. Though the researcher attempted to obtain as diverse a sample as possible, data was primarily collected on university and college campuses and participation in this study was voluntary, which was reflected in the data. The average age of the participants was 24 years old, and with 60.5% of respondents self-reporting 3 hours of more of physical exercise in the last week, participants sampled were younger and more active than expected. However, as the researcher did not specifically target varsity or high-performance athletes, the data is likely still representative of a healthy adult population.

A second limitation of this study was that 3-dimensional motion analysis was not conducted on any participants. Motion analysis would have allowed for calcaneal plantar flexion, which contributes to MLA deformation (Stamm & Chiu, 2015), to be measured for each of the three positions tested on the mirror box. This would have allowed for comparisons of functional arch type results to be made and determine if the mirror box accurately captures changes in MLA height. As recording 3-dimensional motion analysis is time intensive and requires that participants be tested in our research lab, the large volume of required participants prevented this data from being collected. Additionally, the volume of participants required for this study limited the researcher’s ability to retest participants to determine if differences were recorded between days, or with another researcher (Queen, Mall, Hardaker, & Muley, 2007).

Finally, the protocol of the partial squat should be expanded for use in future analysis. A limitation in this protocol was that the researcher was focused on the foot, leg, and torso positions, and did not account for the position of the head and direction of the gaze, specifically whether participants were looking down at their feet or ahead, while data was being collected. The visual system working in conjunction with the vestibular system to coordinate balance, which can shift the center of pressure in the foot and impact MLA height (Neumann, 2013). As this thesis has shown limb and body position to significantly impact overall MLA flattening, the lack of standardization of gaze strategy is a limitation of this research. The effect of gaze strategy must therefore be considered, and better care will need to be taken in future research to ensure that the standardized position includes head and gaze placement in order for results to be comparable.

Future Directions

Research conducted on an individual's arch type is difficult to compare due to the variety of techniques and conditions previously used in data collection. As one of the primary purposes of this study was to establish a set protocol and measurement tool for measuring structural and functional arch characteristics, it is important that this study is repeated, ideally with age- and activity-matched participants, and again with a group of participants more representative of the general population. Doing so can not only provide practitioners with a simple field test for establishing arch type, but also allow for better comparisons to be made between previous research data.

Future research will also need to ensure that special care is taken to standardize gaze strategy, especially in the standing and the partial squat positions where balance is more of a factor. While the partial squat was selected in an attempt to standardize depth between participants in order to ensure generalization, the researcher did not account for the position for the head and the direction of the gaze. Though participants were instructed to look straight ahead, the researcher placed more emphasis on the foot, leg, and torso positions and did not standardize for gaze strategy prior to capturing data.

This study collected data on both hand and foot dominance, but in order to ensure the scope of the thesis was manageable, it was not analyzed. Clinically, dominant limb has been identified as "the leg used to manipulate an object or mobilized to lead out", and preference has been established using a variety of methods including kicking, hopping, step-up tests, and performing dexterous tasks such as picking up pebbles. (Gabbard & Iteya, 1996). This study asked participants to identify their dominant leg by asking which leg they would use to kick a soccer ball. It has been hypothesized that handedness is linked with hemispheric specialization, but due to societal pressures favoring right-handedness, footedness may be a stronger indication of hemispheric specialization (Nachshon, 1983). Previous research has determined that an individual may demonstrate preference for either the left, right, or both (mixed) limbs throughout the course of their life, with a higher proportion of mixed-footedness being observed during childhood (33%) compared to adults (18%) (Gabbard & Iteya, 1996). While the left-handed (6%) and -footedness (8%) of individuals was found to be closely linked in adults, a significantly higher percentage of individuals are right-handed (84%) than right-footed (75%). It would be interesting to study potential differences in structural and functional arch types between feet and their relation to foot dominance in future research in order to truly determine if left and right feet should be pooled in data analysis.

Once this study's methodology has been proven reliable across conditions, future research can begin to determine if specific injuries are more commonly associated with specific arch types. This further leads to research examining if individuals are able to change their structural or functional arch types with targeted training programs. In her thesis research using a training program aimed at increasing calcaneal plantar flexion, von Gaza (2017) found that a combination of a gluteal-hamstring-gastrocnemius raise exercise and self-massage and stretching plantar structures for 6-weeks increased leg dorsiflexion range of motion, likely due to increased calcaneal plantar flexion. If it is found that certain injuries at the knee and hip occur due to limited range of motion at a lower joint, and individuals also tend to have a specific functional arch type, practitioners may then be able to either incorporate training focused on the plantar region, or change or modify the type of footwear an individual is wearing in order to improve movement mechanics higher up the kinetic chain.

Finally, this methodology may be employed to determine if structural and functional arch types are genetic, or the result of activity patterns performed by an individual during growth periods. By studying a variety of high-performance athletes across different disciplines, it might be possible to determine if an athlete is more likely to have a specific structural of functional arch type based on the type of training they do. If it is known that high levels of repeated biomechanically similar tasks make it more likely for an individual to have a certain structural or functional arch type, an arch-specific training program may be provided in order to mitigate potential injuries or allow them to perform tasks more efficiently.

Conclusions

The results from this study show that a simple field tool can be used to capture static and functional characteristics of the MLA. Structural arch data calculated using AI, AA, and Staheli Index matched previously performed research, however, it is important to note that the position of the foot during data collection varied widely between previous studies. Though normal distributions were still observed when using the Chippaux-Smirak Index, the ranges were lower than previously reported, indicating a higher MLA position than previously reported. This could be due to an error in analysis, or perhaps because the theory behind this metric discounts how the wider forefoot evolved to facilitate bipedal walking, and a wider forefoot in relation to the MLA may signify a healthier foot. Arch index used in secondary analysis showed that comparing the structural scores captured while standing or in a partial squat to the unweighted score while sitting can be used to determine functional characteristics of the foot. As similar ranges of change in AI scores were observed in functional data regardless of structural arch type, data was collectively analyzed. Much like structural arch types, there appears to be a range of functional arch types ranging from rigid to flexible. The range of functional changes within structural arch types allows for multiple possibilities of foot types, including a flexible pes cavus foot type, or a rigid normal foot type, or a hyper-flexible pes planus foot type. Because of this variance, an even greater emphasis will need to be placed on the position in which footprint data is collected in order for results to be comparable. Accounting for both structural and functional arch characteristics will allow practitioners to be more targeted when training or treating individuals in the future. The methodology used in this study also showed that the amount of MLA deformation is impacted by the position the body is in, thus requiring standardized positions future data should be captured in if results are to be considered comparable going forward.

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Appendix A: Protocol (Verbal Instructions)

Sitting Position

1. Please sit on the chair and place one foot on each box, toes facing forward
2. In your chair, shift so that your ankle is directly aligned with your knee so that your leg is straight up and down. (Coach participant until you are satisfied with the position.)
3. For the foot on the mirror box, pick up your foot so your toes are in the air and your heel is in contact with the surface.
4. Roll your foot down so that the toes on the outside of your foot (lateral) touch first and big toes touch last. This makes sure that your entire footprint is in contact with the box's surface

Standing Position

1. Please stand up onto the two boxes, moving your feet as little as possible.
2. Balance your bodyweight equally between your two feet, with your arms in a relaxed position by your sides.

Partial Squat Position

1. Please place your hands on your hips and bend your knees as far forward as you can as you move into the partial squat position.
   - Torso must not flex forward and you should try to remain upright
   - Ensure weight your is distributed evenly between L/R feet
2. Do not allow your torso to bend forward. Focus on keeping your back straight.
3. (Non-verbal) Wait until the participant has been in a stable position for at least 10 seconds before taking the photograph.