Variations in the insertions of the tibialis posterior muscle and the structure of the medial longitudinal arch

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SDLMAX001

SUBMITTED TO THE UNIVERSITY OF CAPE TOWN

In fulfilment of the requirements for the degree

MSc (Med) Anatomy

Faculty of Health Sciences

UNIVERSITY OF CAPE TOWN

Date of submission

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Human Biology

DECLARATION

I, Maxwell Sadler, hereby declare that the work on which this dissertation/thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

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Tables, Figures and Graphs

Key terms and abbreviations

1. Abductor hallucis = AH
2. Adult acquired flatfoot = AAF
3. Arboreal/Arboreality = Lives in or climbs trees
4. Arch index = AI
5. *Australopithecus afarensis* = Lucy, 3.0-3.7 million years ago
6. *Australopithecus africanus* = Africanus, 2.0-2.8 million years ago
7. *Australopithecus sediba* = Sediba, about 1.98 million years ago
8. Bipedal = two feet/upright mobility/locomotion
9. Black = People of African origin
10. Cape Coloured = Mixed race individuals with Khoi, white, as well as other ancestries from the many immigrants to the Cape region.
11. Fibularis longus = FL
12. Flexor digitorum longus = FDL
13. Flexor hallucis brevis = FHB
14. Flexor hallucis longus = FHL
15. *Homo sapiens* = Human, anatomically modern 200 000 years ago
16. Lisfranc joint complex = tarso-metatarsal joints
17. Long plantar ligament = LPL
18. Medial longitudinal arch = MLA
19. Pes planus = clinical flatfoot
20. Plantar calcaneonavicular ligament = SL
21. Sustentaculum tali = ST
22. Talus-first metatarsal angle = TFMT
23. Tibialis anterior = TA
24. Tibialis posterior = TP
25. Tibialis posterior tendon = TPT
26. Tibialis posterior tendon dysfunction = pathologies associated with tibialis posterior tendon
27. *Ursus* = Bear
28. Windlass Mechanism = mechanism describing the storing and transferring of energy by intrinsic foot structures such as the plantar aponeurosis.

Acknowledgements

I would like to thank all of the donors who graciously provided their bodies for scientific study. I would also like to thank everyone who has assisted me in my work: my supervisor, Professor Graham Louw, biostatistician Prof. Henri Carrara, statistician Miss Katya Mauff, fellow student Steven Randall for help with the statistical analysis, the laboratory preparers, and all of the second year medical students who performed the superficial dissections down to the ankle. Finally, I must thank my parents, who have always encouraged me and helped me in the pursuit of my academic endeavours.

Abstract

This study utilized cadavers to examine the variable insertions of the tendon of tibialis posterior muscle. Both feet from 29 cadavers were dissected and six variable connections to intrinsic foot structures were documented (frequencies indicated as a per cent): sustentaculum tali (93.1%), abductor hallucis muscle (44.8%), flexor hallucis brevis muscle (22.4%), fibularis longus tendon (58.6%), plantar calcaneonavicular (spring) ligament (17.2%), and the long plantar ligament (34.5%). The frequencies for each variable insertion were also reported individually for sex and population group, as well as the most common combinations of insertions. Measurements describing the medial longitudinal arch of the feet were taken, using a soft tissue intact method (arch index) and the post-dissection method (talus-first metatarsal angle). The insertion data were then compared to the arch measurements, as well as foot side, age, sex, and population group. There was a weak negative correlation between the talus-first metatarsal angle measurement and the presence of an insertion on to sustentaculum tali, as well as a connection to the tendon of fibularis longus. Arch measurements were shown to be statistically significantly similar for left and right feet for each individual. Knowing the arch index on one side of the body allows for an accurate prediction of the arch index on the opposite side within an individual. The right arch index was larger in 55% of the sample. All other correlations were negligible, and the presence or absence of specific insertions was not an accurate predictor of either arch measure. The accumulation of multiple variable insertions did not have any impact on the arch measurements.

Introduction

Background

The belly of tibialis posterior muscle lies in the deep posterior compartment of the leg. It is deep and medial to both the flexor digitorum longus (FDL) and flexor hallucis longus (FHL) muscles, arising from the medial-posterior portions of the tibia and fibula, as well as the interosseus membrane. The tibial nerve innervates the tibialis posterior muscle (TP), and the posterior tibial artery supplies blood. The tendon (TPT) forms in the distal third of the leg where it runs adjacent to the tendons of flexor digitorum longus and flexor hallucis longus. Tibialis posterior tendon runs closest to the medial malleolus of the tibia, with the tendon of flexor digitorum longus adjacent (flexor hallucis longus takes a different path, running below the sustentaculum tali). At this location, the histological make up of the tendon changes, flattening, its composition transitioning to contain more fibrocartilage, as well as becoming more avascular (Semple et al., 2009). This hypovascular region may be a contributor to the relatively high prevalence of tibialis posterior tendon dysfunction, which is typically localized in this area (Gluck et al., 2010). The bony insertions of tibialis posterior tendon are well documented and generally agreed upon in the literature, however there exists several variable insertions into soft tissue structures that are not as extensively documented. Several studies have documented various soft tissue insertions; however further work will only expand the knowledge on the frequency of such insertions. Additionally, the source of this variability, as well as the structural significance of the variations remains unknown.

Tibialis posterior plays an integral role in the biomechanics of bipedal locomotion. It is the main extrinsic supporter of the medial longitudinal arch (MLA), and so its insertions into the plantar aspect of the foot are integral in its proper functioning (Semple et al., 2009). Furthermore, many debilitating ailments associated with pes planus and tibialis posterior tendon dysfunctions occur, indicating the intimate relationship between tibialis posterior and the medial longitudinal arch, as well as their importance in healthy locomotion (Gluck et al., 2010). The anatomically modern human foot has three arches; the medial longitudinal, lateral longitudinal, and transverse (see figure 1). This arched structure was a crucial specialization in the development from quadripedal and arboreal locomotion to bipedal locomotion, and are a defining characteristics that define the *Homo sapiens* species (Zipfel et al., 2011). These three arches serve many purposes, with the medial longitudinal arch being the most critical to normal and healthy gait. The medial longitudinal arch acts as a spring, or "shock absorber," under load, as well as functional synergy with other intrinsic foot structures, such as the plantar aponeurosis, absorbing, storing, and transferring energy (i.e. Windlass Mechanism) (DeSilva et al., 2010). In the shock absorption phase of gait, tibialis posterior is the main extrinsic muscle responsible for slowing and controlling the deformation of the medial longitudinal arch (Ferber et al., 2011). Several pathologies are directly related to tibialis posterior tendon dysfunction, inhibiting tibialis posterior in performing this task. Additional pathologies exist relating to medial longitudinal arch heights and flexibilities that are not within the ideal range, especially in athletes that engage in sports requiring running (DeSilva et al., 2010). The relationship between tibialis posterior and the medial longitudinal arch coupled with the prevalence of pathologies related to their dysfunction indicates the importance in having a thorough understanding of the specific anatomical attributes.

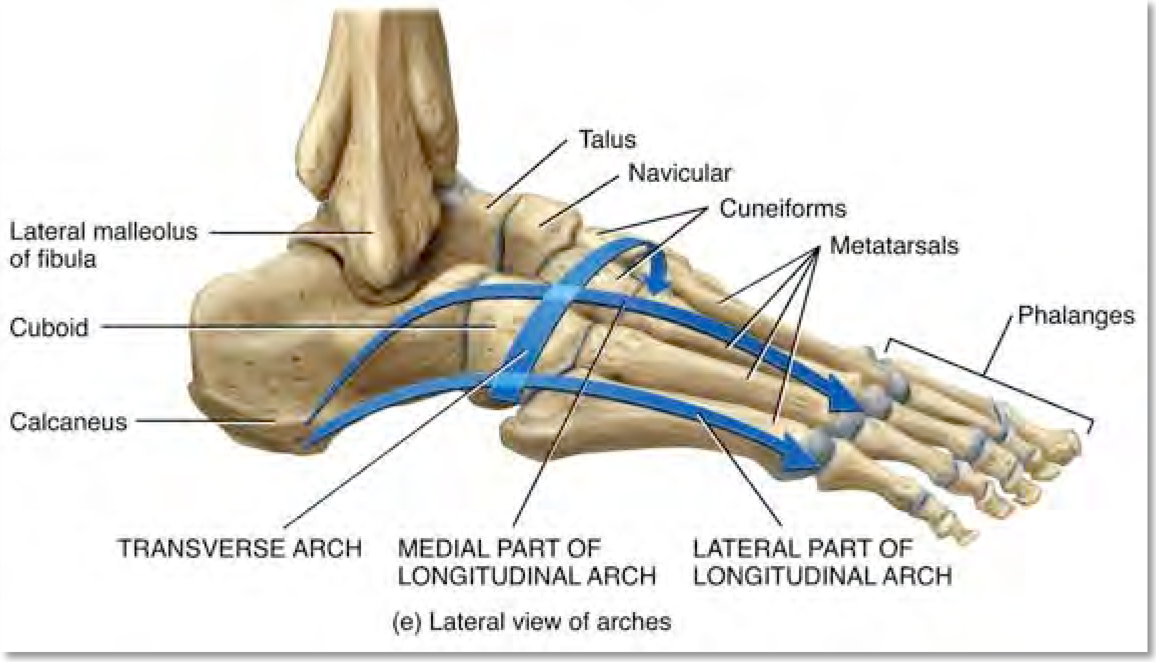

Figure 1Drawing showing the three arches of the foot (http://www.studyblue.com).

The first insertion of the tibialis posterior tendon is to the navicular tuberosity, where the tendon also splits into anterior, middle, and posterior bands. The anterior band is the largest and continuous with the main tendon, inserting into the navicular tuberosity, naviculocuneiform joint capsule, and inferior surface of the medial cuneiform bone. Although there is some disagreement on the prevalence, a fibrocartilaginous or bony sesamoid may also be present within the anterior band at the insertion of the navicular bone (Bloome et al., 2003). Semple argues that this sesamoid may act to absorb pressure or as a gliding mechanism, but accessory navicular can also be a debilitating pathology (Gluck et al., 2010). The middle band of tibialis posterior tendon inserts to the plantar surface of the middle and lateral cuneiform bones, the cuboid bone, and metatarsals 2-4. The posterior band branches 2-3 mm proximal to the anterior band, travelling posteriorly and plantarly, helping to form the acetabulum pedis. The bony insertion of the posterior band is to the sustentaculum tali (ST) (Bloome et al., 2003).

Variations in tibialis posterior insertion

Along with the aforementioned insertions, several variable insertions to bony and soft tissue structures exist that are often omitted from the literature. A bony insertion to the base of the fifth metatarsal has been shown, although it is not always documented (Myerson et al., 1999). Numerous soft tissue connections have also been documented, with varying frequency, whose functional importance is not understood. In the anterior band, connections to abductor hallucis (AH) have been shown in previous studies with a 45% rate of occurrence (Bloome et al., 2003). The middle band contains the most variation, with slips connecting tibialis posterior tendon to fibularis longus (FL) and flexor hallucis brevis (FHB), as well as the aforementioned variability with fifth metatarsal attachment (Sarrafian, Bloome, Martin, Pastore, Sanal). Many of the insertions blend with the overall ligamentous structure of the medial longitudinal arch (Pastore et al., 2007). Martin also documented a distinct connection to the fibres of the long plantar ligament (LPL). Finally, Bloome and Martin also have shown a connection to the plantar calcaneonavicular (spring) ligament (SL). The frequency of these variable insertions is not entirely known, with few studies focusing on determining the prevalence of the variations. Likewise, the structural significance is not known, although it has been proposed that the slip to fibularis longus may contribute to the Lisfranc joint complex (Sanal et al., 2011).

Functions of tibialis posterior

The actions of tibialis posterior muscle in general terms are inversion of the foot, plantarflexion at the ankle joint, and hindfoot (define this terminology) supination, however the practical applications of these actions are much more complex. Tibialis posterior is responsible for locking the transverse tarsal joint by hindfoot inversion after heel strike, thus creating a rigid midfoot in the middle stages of foot strike that is necessary for normal gait (Bloome et al., 2003). Without this locking mechanism, the efficiency of gate is greatly reduced due to the inhibition of gastrocnemius (Kohls-Gatzoulis et al., 2004). The general functions of tibialis posterior are necessary in normal walking and running, as they allow for the maximal effectiveness of other propulsive muscles, as well as shock absorption through pronation. In most humans, pronation acts to move the foot from a lateral heel strike to a hallux toe off, and tibialis posterior is the main dynamic controller of this motion (Morley et al., 2010).

Studies have shown that applying tape in such a way as to reduce pronation raises medial longitudinal arch height and decreases tibialis posterior activity, showing the direct relationship between the motion of pronation, the height of the medial longitudinal arch, and the action of tibialis posterior (Franettovich et al., 2008). Additionally, fatigue in tibialis posterior is associated with an increase in excessive pronation as well as movements in other joints in the foot, pointing to a mechanism for overuse injury (Ferber et al., 2011).

Evolution and tibialis posterior

A progressive expansion and increase in complexity of the insertion of the tibialis posterior tendon is evident upon examination of the muscle in other primates. In the reptilian homologue of tibialis posterior, the tendon connects to the mammalian homologue of the tibia (Lewis, 1964). This connection is represented in most extant mammals by the navicular tuberosity or the tibial navicular bone. Prosimii and certain New World Monkeys display this more primitive insertion, as well as some lateral prolongation into the sole of the foot in some species. Old World Monkeys display this lateral prolongation to a greater extent, with connections to the bases of metatarsals two, three, and four. In all of the aforementioned primates, the internal Y-shaped ligament is superficial and separate from the tendon of tibialis posterior. Pongidae, especially *Pan,* begin to show a fusion between the tibialis posterior tendon and the Y-shaped ligament, thus adding additional attachments for tibialis posterior. The additional connections to other soft tissue structures that are evident in *Homo* may indicate a continued evolution of tibialis posterior as well as its progressively important role in bipedalism, and in the development of an arched foot. The increasing number of plantar insertions and the synergistic effects from connections to intrinsic foot muscles enhance the upward lifting of the arch of the foot by tibialis posterior (Lewis, 1964).

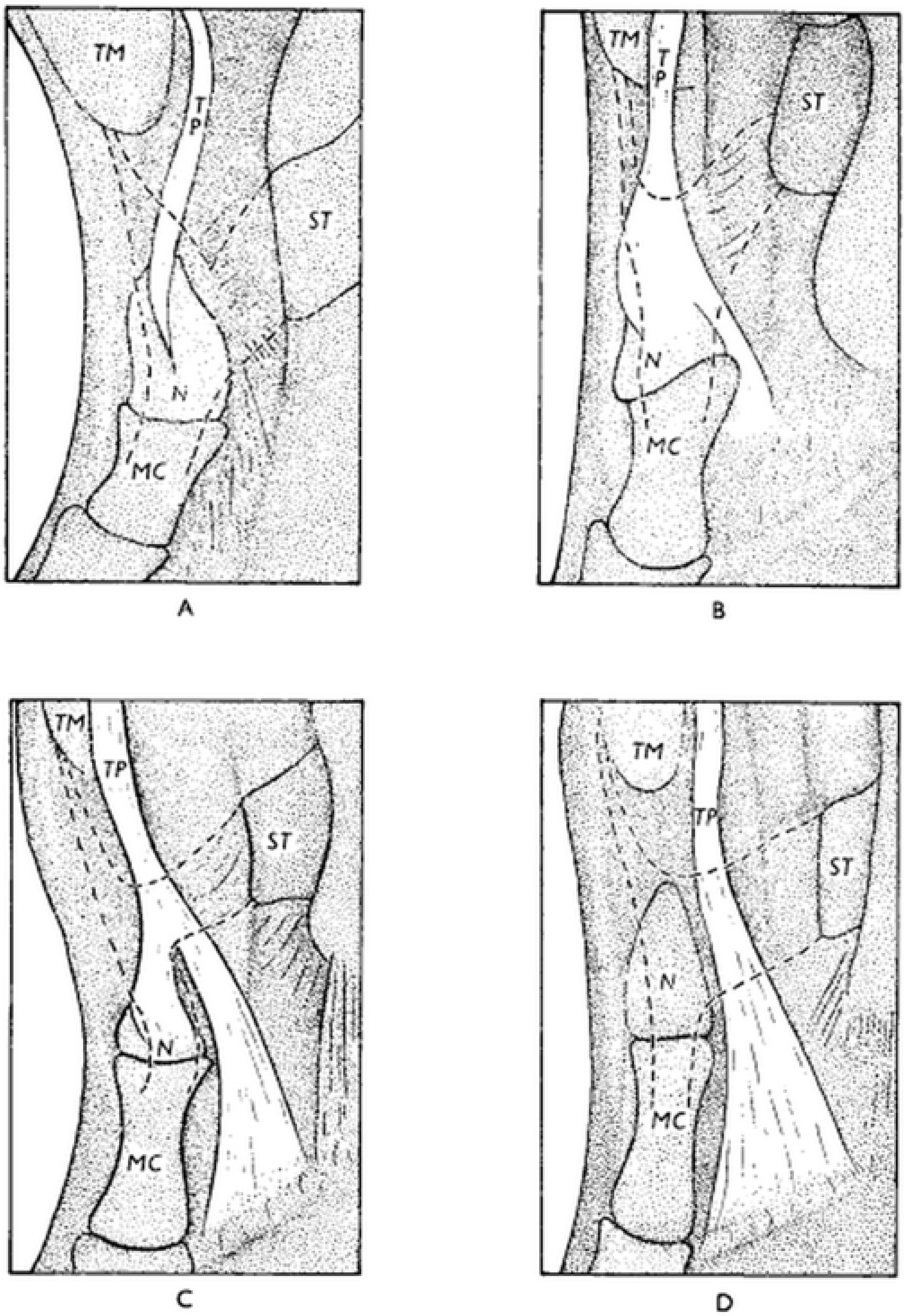

Figure 2 Insertion of TPT in various primates. A: *Pithecia monachus* (Monk saki, New World), B: *Cebus nigrivittatus* (Wedge-capped capuchin, New World), C: *Cercopithecus nictitans* (Greater spot-nosed monkey, Old World), D: *Colobus polykomos* (King colobus, Old World). Tibialis posterior (TP), sustentaculum tali (ST), navicular (N), and medial cuneiform (MC) are all labelled. From A to D, the TPT transitions from that of one that is more similar to reptiles to one that is more similar to hominins. The Y-shaped ligament is indicated by dashed lines, and in these cases is a separate structure, where as in modern humans has become fully integrated with the TPT (Lewis, 1964).

Other plantigrade mammals, such as *Ursus* (bear) are typically only opportunistically bipedal. The structure of the foot in bear differs greatly from that of *Homo sapiens* (humans), and their reason for bipedalism is more to reach up high for food, for enhanced vision, and other reasons (Hildebrand, 1995). The tibialis posterior homologue in plantigrade mammals such as bear does not display the same complexity of insertion or the same function as that of humans, where the most important function is that of an extrinsic supporter of the medial longitudinal arch. The three arches of the foot are significant contributors to the efficiency of bipedalism. When bears stand on two feet, they are typically relatively stationary, and so the plantigrade structure of their foot is sufficient for the task at hand. Humans, on the other hand, stand, walk, and run on two feet, and so efficiency of gait is of the utmost importance. The intimate relationship between the action of tibialis posterior and the medial longitudinal indicate its importance in the development of bipedalism. Whereas bipedalism in humans may have developed through numerous mechanisms for several reasons[1], a foot structure conducive to prolonged standing, walking, and running is a keystone feature of this human adaptation. Humans are the only obligate bipedal primates currently in existence, and the insertion of tibialis posterior is also much more complex than that of other primates and mammals. Many adaptations exist that contribute to the efficiency of gait, and the speed of locomotion, both in quadripedal and bipedal animals. Many animals, including bipedal birds like *Struthio camelus* (ostrich) and the quadripedal mammal Ungulates, are

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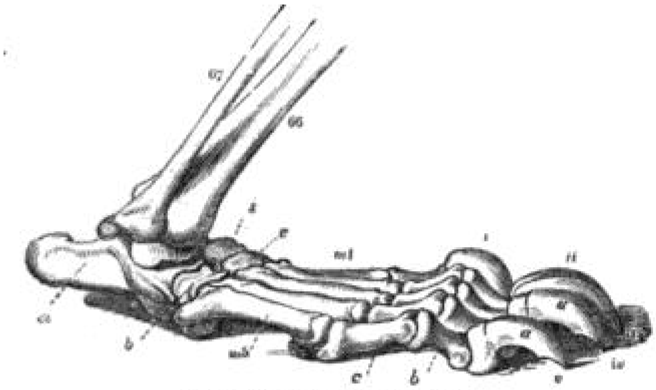
[1] Several theories exist, such as the minimal cost of transport theory, the advantages of freeing up the forelimbs for tool use, and the ability to spot predators easily. In all likelihood, it was some combination of all the various advantages that lead to the development of bipedalism as an obligate behaviour.

digitigrade, which elongates their legs, thus increasing stride length and therefore speed/efficiency (Hildebrand, 1995). Humans exhibit a unique adaptation in that the arched foot acts as a propulsive shock absorbing spring mechanism, rather than resorting to the elongation of distal leg and foot bones and obligate digitigrade locomotion[2].



Plantigrade foot, hind limb, Bear.

Figure 3 Bears are plantigrade mammals that are opportunistically bipedal, with very different adaptations in foot structure compared with humans. As shown in this figure, all foot bones are in contact with the ground, contrasting with humans, where the calcaneus, metatarsal heads, and phalanges make ground contact while the majority of the metatarsal and tarsal bones create the transverse, medial, and lateral longitudinal arch structures (Owen, 1866).

Evolution of the arched foot

The transition from an arboreal lifestyle found in early, pre-hominin species, to a terrestrial, bipedal lifestyle like that of modern humans, was one of the crucial adaptations in defining the genus *Homo*. Critical to bipedal locomotion was the development of a longitudinally arched foot (DeSilva et al., 2010). Transverse foot arches are found in all primates, whether they are quadripedal, arboreal, or bipedal. Longitudinal arches, however, are only found

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[2] Top-end speed sprinting of humans is typically achieved by running on the forefoot or toes, similar to that of other digitigrade animals that are significantly faster than humans over short distances. The efficiency of the arched foot really shines in endurance type running, where humans outpace many other animals, especially other bipedal animals. Humans exhibit many energy saving adaptations that aid in endurance running, and the structure of the arch is one such adaptation.

in bipedal hominins, of which, only humans remain living (DeSilva et al., 2010). The arch is a supported by the ligamentous architecture of the foot, as well as extrinsic muscles, most importantly tibialis posterior. Evidence for many of these ligamentous structures, such as the long plantar ligament, is present in many pre-*Homo* hominins. Although there is little agreement on just when, how fast, and what patterns there are regarding the development of the longitudinal arch in early hominins, it is agreed that its existence is a crucial adaptation for bipedalism and a defining characteristic of modern humans (DeSilva et al., 2010). One such specimen, the *Australopithecus afarensis* fossil popularly known as Lucy, can be interpreted as having a flat or slightly arched food based on various characteristics of the bones that are available and their relationships to one another. By analysing the tibial arch angle, DeSilva et al. concluded that *Au. afarensis* had an arched foot, albeit with a high degree of variability. Non-human primates have a posteriorly directed tibial arch angle, while most humans have an anteriorly directed tibial arch angle[3] (see figure 3). As non-human primates do not have a longitudinally arch foot, and modern humans do, it is thought that an anteriorly directed tibial arch angle is indicative of the presence of a longitudinal arch. Most importantly, despite the possibility that Lucy's foot was flat, it may have been without the problems that are associated with flat footedness in modern humans, and other *Au. afarensis* fossils show with greater certainty the existence of an arched foot, indicating a possibly high degree of variability within the species. Furthermore, the prevalence of asymptomatic flat footedness may have been much higher in Lucy and her contemporaries than in

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[3] Interestingly, a small percentage of the modern human population has a posteriorly directed tibial arch angle (~8%), and these individuals express asymptomatic flatfoot.

modern humans (DeSilva et al., 2010). Drapeau et al. analysed the metatarsals on another *Au. afarensis* sample, noting that a strongly everted third metatarsal is representative of a longitudinal arch. This *Au. afarensis* sample had a strongly everted lateral foot, which may suggest the development of a longitudinal arch (Drapeau et al., 2013).

Other pre-*Homo* samples, such as *Australopithecus sediba* (Sediba) and *Australopithecus africanus* (Africanus) show this same degree of variability regarding the structure of the arch. A fossilized Sediba talocrural joint from Malapa, South Africa, shows many features indicative of an arched foot. The distal end of the tibia of Sediba exhibited an anteriorly directed tibial arch angle of 6.7 degrees, which as previously stated indicates that the foot is arched (Zipfel et al., 2011). In addition, the talar neck and head were angled toward the plantar surface of the foot, as well as the cuboid facet (as in modern humans) also suggesting an arched foot. All in all, the articulations of the astonishingly well preserved articulated tarsal and distal tibia bones exhibit features that are strongly indicative of an arched foot. Also of note is the relative robustness of the medial malleolus of the tibia, which suggests that it was more weight bearing than in modern humans, which may indicate that Sediba's foot was arched, although somewhere in between that of modern humans and other hominins. Interestingly, the same sample also has features indicating some degree of arboreality, suggesting that the transition from an arboreal lifestyle to a terrestrial, bipedal one may have been a gradual process, with the development of the longitudinal arch coinciding with this change (Zipfel et al., 2011). Although the relative rarity of early hominin distal limb fossils and footprints makes it difficult to conclusively say to what degree pre-*Homo* species had a longitudinally arched foot, it does seem apparent that the transition from an arboreal to a bipedal lifestyle ran parallel to the development of an arched foot, and that the longitudinal arch was in fact a critical component to this change. Furthermore, the relatively recent switch from an arboreal and quadripedal lifestyle to that of a bipedal one may suggest the reasons for such variability in the arches of modern humans, as well as the high degree of complexity and the several variations in tibialis posterior tendon insertions that are presently found.

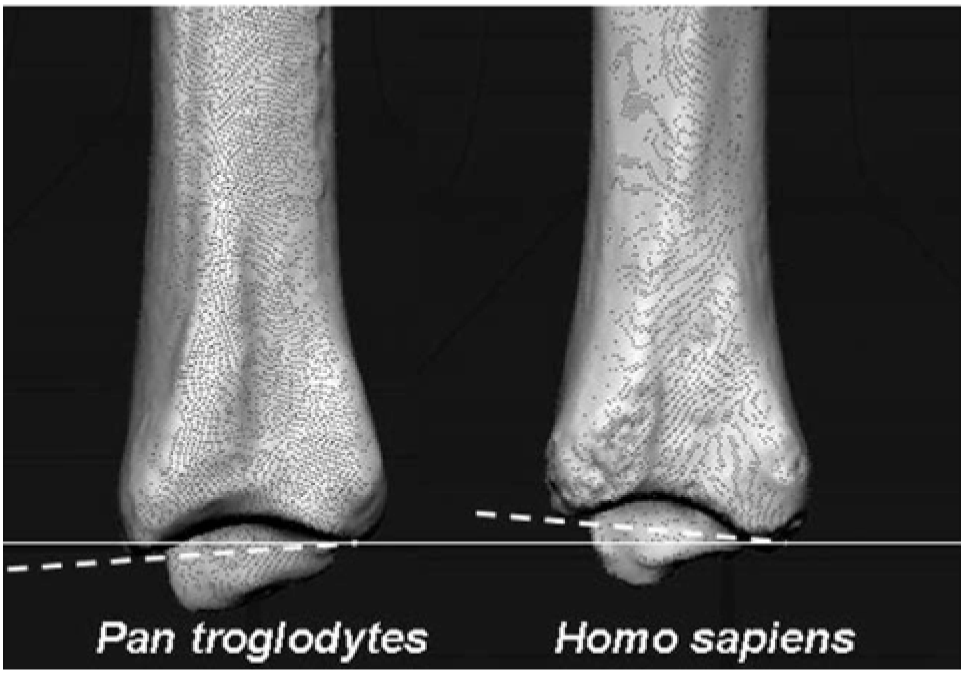

Figure 4 Tibial arch angles between *Pan troglodytes* (Chimpanzee) and *Homo sapiens* (Human). While Chimpanzees exhibit a posteriorly directed tibial arch angle (towards the right), like modern humans, Lucy had an anteriorly directed tibial arch angle (towards the left) (DeSilva et al., 2010).

Figure 5 Modern human calcaneus (top right) compared to the digital model of the Sediba calcaneus (second row, left). Several of the defining characteristics that were compared are shown. The lateral plantar process (LPP) and medial plantar process (MPP) of Sediba are rather ape-like, but the cuboid facet of Sediba, indicated by the bracket, is more human like (Zipfel et al., 2011).

Pathologies of the tibialis posterior tendon

Many conditions are associated with tibialis posterior dysfunction, including, but not limited to, accessory navicular, adult acquired flat foot (AAF), tendon degradation, and tendon rupture.

Accessory navicular

A fibrocartilaginous or bony accessory navicular is frequently[4] found embedded in the tibialis posterior tendon at the navicular insertion. Accessory navicular is classed as Type 1, Type 2, or Type 3, with varying degrees of

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[4] Can be unilateral or bilateral. Typically develops after five years of age and is most common in early adolescents. Significantly more prevalent in females. Exact frequencies of occurrence are not well known.

severity[5] (Gluck et al., 2010). Additionally, tibialis posterior tendon can occasionally insert only into the accessory navicular, without any continuity into the remainder of typical tibialis posterior tendon insertions (Fernandes et al., 2007). The resulting inability of tibialis posterior tendon to support the medial longitudinal arch due to its inadequate insertion is often associated many degenerative changes and pes planus (Pastore et al., 2008).

Tibialis posterior tendon dysfunction

Tibialis posterior tendon dysfunction is associated with the progressive degradation of tibialis posterior tendon, and is broken into four categories. Type I is accompanied by tenderness at the location of navicular insertion, variable oedema and warmth, and tendinosis or tenosynovitis. Type II brings about gradual pes planus deformity, combined with a varying degree of heel valgus. Type III begins when flexibility is lost due to hindfoot deformity and lateral ankle pain increases. Forefoot supination typically occurs as a measure of compensation. Degenerative changes in subtalar, talonavicular, and calcaneocuboid joints occur. When Type III is not corrected, it can progress to Type IV, when ankle arthrosis begins (Gluck et al., 2010).

Tibialis posterior tendon rupture

Chronic overuse can result in the rupture of tibialis posterior tendon. Although many techniques for repairing this tendon rupture exist (such as using the tendon from flexor hallucis brevis), healing can be slow and incomplete due to the poorly vascular nature of the tendon at the location of rupture. The

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[5] Type 1: Ossicle within substance of TPT. Type 2: Synchondrosis joining accessory navicular to the navicular bone. Type 3: Fused to navicular. All three conditions can produce varying degrees of pain as TPT is active.

resulting overload on midfoot ligaments leads to progressive talus deviation into flexion and adduction, ultimately leading to osteoarthritis (Fernandes et al., 2007).

Pathologies associated with medial longitudinal arch

Dysfunction of the tibialis posterior tendon is the primary cause of adult acquired flatfoot, a debilitating condition that when left untreated results in arthritis, loss of mobility, and severe pain (Bloome et al., 2003). Rather than attaching to one bone across one joint, tibialis posterior tendon inserts on all of the midfoot bones, and many forefoot bones, crossing many joints. The resulting inability of tibialis posterior to control movement in several joints leads to excessive motion that is detrimental (Ferber et al., 2011). It is difficult to say exactly what occurs first in adult acquired flatfoot, whether it is the degradation of intrinsic foot ligaments, tibialis posterior tendon injury and resulting dysfunction, or arch deformation for another reason. What is certain is that tibialis posterior tendon dysfunction alone is not enough to produce static deformation, and each component of adult acquired flatfoot compounds the other issues (Gluck et al., 2010). As tibialis posterior tendon function decreases, the excessive wear on intrinsic foot ligaments (spring, deltoid, talocalcaneal, talonavicular capsule, and plantar aponeurosis) causes further arch deformation, thus putting even more strain on tibialis posterior tendon. In an attempt to correct for the pes planus deformity, tibialis posterior tendon recruitment in the stance phase[6] is greatly increased, as shown by EMG studies (Semple et al., 2009). Abnormality in the medial longitudinal arch is often thought to be a predictor of

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[6] TPT activity in stance phase is negligible and in balance with PL activity in individuals with a normal functioning arch.

injury, especially overuse injuries in activities involving extensive running or walking (Williams et al., 2000). Furthermore, individuals with pre-existing pes planus who engage in physical activity will inevitably recruit tibialis posterior more than would individuals with a normal arch, which could lead to tibialis posterior tendon dysfunction. The recruitment of other muscles in an attempt to compensate for the inability of tibialis posterior to control excessive foot motion could also lead to muscle pain and overuse injuries associated with the additional muscles in question.

Relationship between tibialis posterior tendon insertion and medial longitudinal arch

The anatomical structure of the medial longitudinal arch is highly variable in modern humans. It varies greatly in height and flexibility, with myriad conditions that can result from these variations. Although arch structure and height ranges greatly within the human population, there are characteristically low and high arches on either extreme of the mean that can be indicated in an increased prevalence of pathology (for example, talus-first metatarsal angles that are greater than four degrees have been linked to symptomatic pes planus in adults) (Villarroya et al., 2008). Due to the intimate relationship between the medial longitudinal arch and the tibialis posterior tendon, and their complex variability, it can be assumed that there may exist some correlation between medial longitudinal arch structure and variations in insertions of the tendon. That is to say, the presence of specific variable insertions, or a cumulative effect of having more of these variable insertions, may lend to some measureable effect in the ultimate structure of the medial longitudinal arch. The dependent relationship between both the medial longitudinal arch and tibialis posterior becomes evident upon careful examination of tibialis posterior activity in biomechanical analysis. While a pes planus foot has a navicular bone that is closer to the ground, thus increasing the length of the tibialis posterior musculotendinous unit, adaptation is shown by an increase in the number of sarcomeres and the recruitment of other muscles. Conversely, adding a foot orthoses to raise navicular height increases selective activation of tibialis posterior. Individuals with a normal arch exhibit increased tibialis posterior activity, indicating the proper functioning of the tibialis posterior tendon-medial longitudinal arch complex (Kulig et al., 2005).

Aim of Study

The purpose of this study was to add to our understanding of the frequencies of variable tibialis posterior tendon insertions. In addition, arch index (AI) and talus-first metatarsal angle (TFMT) measurements were taken in an attempt to delineate the potential structural significance of variable insertions of tibialis posterior tendon. Previous studies have not reported on frequencies of variable insertions with respect to foot side, sex, age, and population group. This study ignored arch flexibility to focus solely on arch structure in an attempt to illuminate a correlation between specific insertions and arch structure, or perhaps a cumulative effect of variable insertions. I hypothesized that having more variable insertions would result in an arch structure that is closer to ideal, or at least within the average to high range, compared to the absence of variable insertions, which may result in a compromised arch structure. I also anticipated that the absence of a specific insertion would result in a lower arch. I did not anticipate there to be any differences in insertion variation or arch measures between foot side, sex, or population group. I expected arch index values to decrease and talus-first metatarsal angle to increase as a function of age, as previous studies have shown arch height to gradually decrease with age as a result of the effects of gravity and general wear and tear on the ligaments within the foot.

Methods

Sample

The left and right feet from 29 cadavers were utilized, of which 18 were male and 11 were female (N = 58). The population groups of the sample consisted of 15 “Cape Coloured” (Mixed-Race), 11 White, and 3 Black. These population group distinctions are remnants from the Apartheid government, where the Population Registration Act of 1950 defined the South African population into four groups: White, Native/Bantu/Black, Coloured, and Asian (Patterson et al., 2010). The Coloured individuals used in my study were those that fit into the genetically distinct population group consisting of white, black immigrants, local Khoi, and Indonesian ancestry (Henneberg, Louw, 1998). White individuals are of European origin, without any Sub-Saharan African genetic contributions. The ancestry of Black individuals consists of Bantu-speaking peoples who migrated into South Africa from other Sub-Saharan areas (Tishkoff et al., 2002).

The ages at the time of death ranged from 29 to 97 years with an average age of 61 and 10 months, of which 14 cadavers were under the age of 55 and 15 were over the age of 55 (see table 1). The cadavers were either donated with written consent to the University of Cape Town, or were paupers, in which case the Department of Health granted permission for educational purposes.

Cadaver #	Sex	Age	Population group
2812	F	29	Mixed
8212	M	30	Mixed
8712	M	34	Black
2712	M	38	Mixed
6112	F	40	Mixed
6912	M	41	Mixed
5312	M	41	Mixed
6212	F	42	Mixed
812	M	44	Black
4012	M	45	Mixed
7712	F	47	Mixed
4812	F	48	Mixed
4712	M	50	Mixed
7212	M	53	White
5412	M	59	Mixed
6412	M	60	Mixed
8611	M	62	White
3812	M	63	Mixed
5012	F	74	Mixed
4512	M	78	White
4912	M	81	Black
3712	F	85	White
8911	M	87	White
5612	M	91	White
8912	F	92	White
3312	F	92	White
5812	F	94	White
8012	M	96	White
5912	F	97	White

Table 1 Cadaver identifier, sex, age, and population group.

Arch index

Arch index measurements were taken prior to the removal of the skin, as these types of measurements are typically used in a clinical setting on live subjects with skin and muscles intact. Arch index is determined by dividing truncated foot length by dorsum height at 50% of total foot length[7] (Saltzman et al., 1995). Foot length and truncated foot length were measured using a ruler and placing the heel on the dissection table. Dorsum height was measured using callipers, with the ruler as the base and placing the callipers at 50% of total foot length. The reason an arch index is used as opposed to arch height is to normalize for foot length and varying toe length. Previous studies have shown this to be a much more effective and accurate means to determine the height of the arch (Williams et al., 2000). Furthermore, by taking the measurements with skin and muscles in tact, a clinical setting could best be replicated.

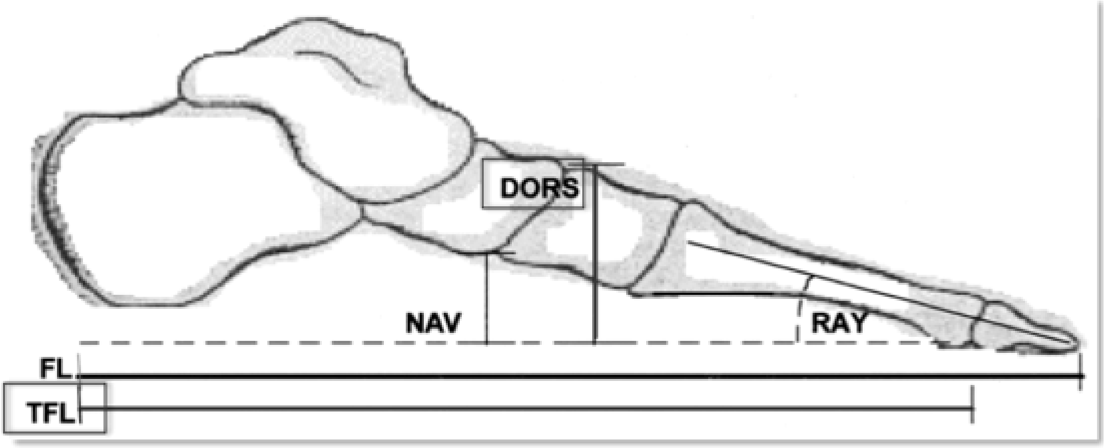

Figure 6 Figure showing measurements used for AI. NAV describes the measure in height between the horizontal base line and the base of the navicular bone. DORS refers to the measure of horizontal base line to dorsum of the foot, and RAY to the angle between the floor and the longitudinal axis of the metatarsals in the standing position (Williams, 2000).

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[7] Total foot length is defined by most posterior aspect of the calcaneus to the most distal phalanx. Truncated foot length is the measurement from the most posterior aspect of the calcaneus to the first metatarsophalangeal joint. Dorsum height is measured at 50% of overall foot length, and is from the base (ground in living, standing subjects) to the dorsum of the foot.

Dissection

Dissection began by exposing the tibialis posterior tendon at the level of the medial malleolus, and then tracing it down to its first bony insertion, the navicular tuberosity. Any slips connecting the tibialis posterior tendon to abductor hallucis and flexor hallucis brevis were noted. Next, the superficial layers of the plantar foot surface and abductor hallucis muscles were reflected, exposing deep muscles, the sustentaculum tali, and the spring ligament. Slips connecting tibialis posterior tendon to the sustentaculum tali and the spring ligament were noted before reflecting the deep muscles. At this level, slips connecting tibialis posterior tendon and the long plantar ligament could be observed. Finally, the fibularis longus tendon was exposed starting at the fifth metatarsal, tracing it medially and anteriorly to its insertion at the head of the first metatarsal. Adjacent to this location, slips connecting tibialis posterior tendon to fibularis longus were observed.

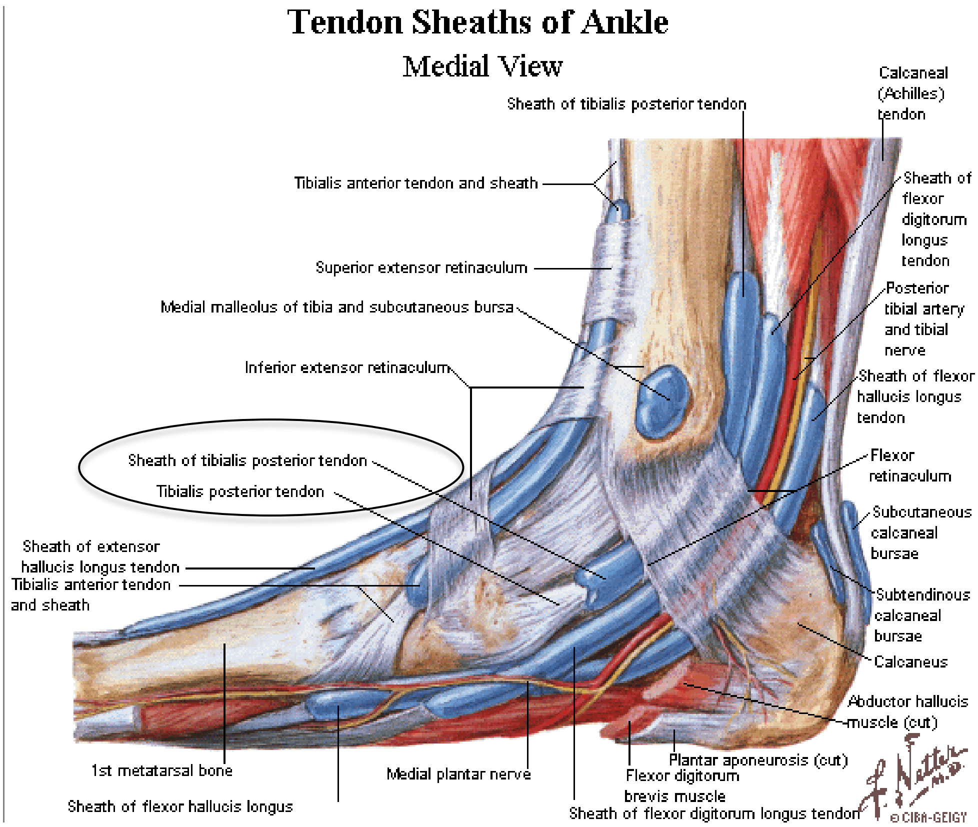

Figure 7 Medial aspect of the ankle and foot showing where dissection would start, tracing TPT from the medial malleolus of the ankle to its various insertion points (Netter, 2006).

Talus-First Metatarsal angle

After dissecting, photographs[8] of the medial side of the foot were taken. The feet were placed in moulds made out of florist's foam in order to orientate and stabilise all feet in the same way. Two moulds were made, one each for left and right. Markers were placed indicating the orientation of the longitudinal axis of the talus and the first metatarsal. These photographs were then uploaded into iPhoto[9] where they were cropped to the same size, and when necessary rotated to align with the horizontal plane. The angle between the longitudinal axis of the talus and the first metatarsal was then measured using PixelStick[10]. This

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[8] Nikon Coolpix® L20 digital camera. Copyright © 2011 Nikon Corp.
[9] iPhoto '11 version 9.5 (902.7). Copyright © 2002-2013 Apple Inc.
[10] PixelStick version 2.5. Copyright © 2013 Plum Amazing, Llc.

additional measurement is typically used in clinical settings, although the procedure differs, namely radiographs versus photographs. Previous studies have shown that measuring this angle on radiographs is a good indicator of arch structure (Younger et al., 2005). In clinical settings, it is also an effective means of determining the deformation that occurs in the bony structure of the foot as a result of the flexibility between foot bone joints. Because the skin and muscles was removed on the cadavers, the same technique could be applied without radiographs in this study.

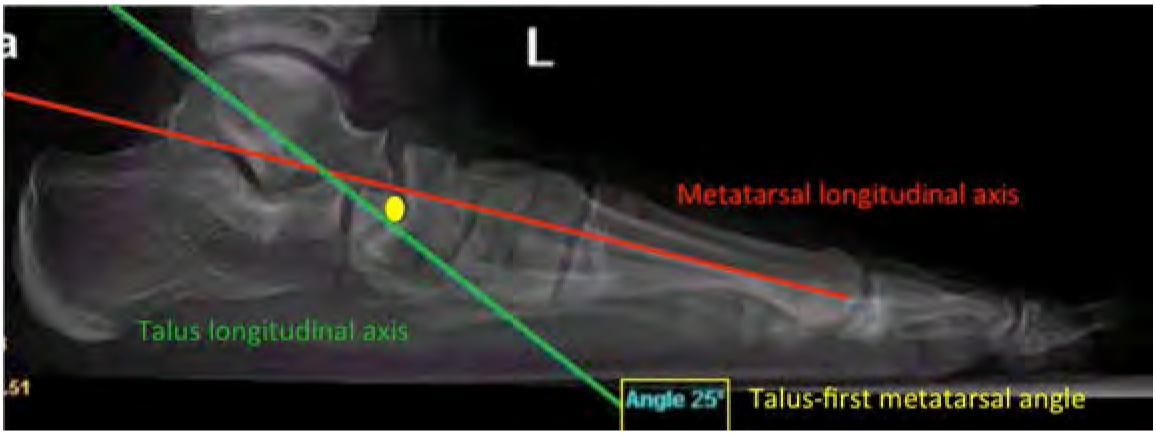

Figure 8 Radiograph showing axes used and angle measured for TFMT Angle (Villarroya, 2008).

Figure 9 Photograph showing florist's foam attached to wooden backing, before mould for foot was cut out.

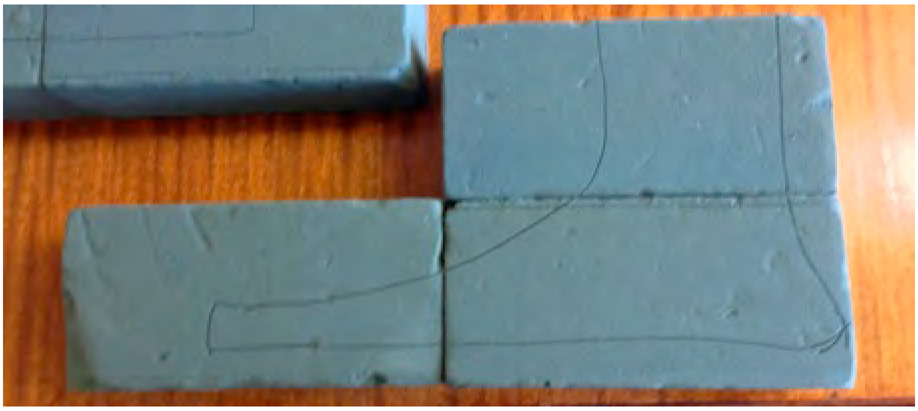

Figure 10 Photograph showing construction process of foot mould.

Figure 11 Photograph showing mould after foot shape was cut out.

Figure 12 Photograph showing implementation of foot mould with cadaver foot in place and pins placed on bony landmarks.

Explanation of measurements

Arch index and talus-first metatarsal angle measurements were chosen due to the slightly different information they provide, their ability to be extrapolated to living, weight-bearing subjects, and their frequent and effective use in clinical settings. The arch index measure accounts for the aspect of the arch that may be made up of soft tissue, as these certainly have an effect on the practical function of the arch. Talus-first metatarsal angles ignore soft tissue to a certain extent and focus specifically on the bony arch structure. The use of these two measures in conjunction will help to determine just how tibialis posterior may affect the structure of the medial longitudinal arch.

The values for arch index were higher, and talus-first metatarsal angle more negative (indicating a higher arch) than what is typically reported in clinical use due to the fact that these measurements were taken in a non-weight bearing, cadaveric sample. Additionally, the embalming chemicals used on the cadavers results in some shrinking of soft tissues, which will cause the arches to rise. All the cadavers were embalmed in the same way using the same chemical formula (and have all been embalmed for the same length of time), so this shrinkage effect is consistent for all samples. Finally, the arch measures are reliable in comparing arches within this sample, as they are all measured in the same way. The data can certainly be extrapolated to a living, weight bearing situation. Arch deformation studies have shown that although arch index and talus-first metatarsal angle do change depending on the per cent of body weight that is being applied, the categorization of “low” and “high” arches remains the same[11]. What is considered a "low" arch in comparison to other arches within the sample will, under low weight bearing conditions remain a "low" arch as it will under high weight bearing conditions as well (Razeghi et al., 2002). A similar pattern is also seen with high arches.

Statistical Analysis

All data were analysed in SPSS[12]. Tests for normality and descriptive statistics were performed on all variables. Collinearity was checked to ensure that there were no collinearity issues. Linear regression models were performed to check for relationships, and the standard errors were adjusted for clusters within the data. Each measurement was performed on both the left and right feet of every sample, and since there is less variation within a sample than between samples, the data was clustered for each cadaver when performing the linear regressions. Relationships between each individual variable insertion were compared to age, sex, population group, arch index, and talus-first metatarsal angle using linear regression. In addition, relationships between the cumulative numbers of insertions were compared to age, sex, population group, arch index, and talus-first metatarsal angle using linear regression. Pearson correlation tests were performed in order to check for correlations between the dependent variables (arch index and talus-first metatarsal angle) and the hypothesised predictors (age, sex, population group, sustentaculum tali, abductor hallucis, flexor hallucis brevis, fibularis longus, spring ligament, and long plantar

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[11] Other studies have shown that arch flexibilities do in fact differ, however the use of both AI and TFMT measurements, which include and exclude soft tissue respectively, counteracts this effect.

[12] IBM Corp. Released 2012. IBM SPSS Statistics for Mac, Version 21.0. Armonk, NY: IBM Corp.

ligament). Scatter plots were constructed to visualize age versus arch index/ talus-first metatarsal angle. Box plots were constructed to visualize the arch index/ talus-first metatarsal angle with sex and population group.

Results

Variable insertions

Sustentaculum tali

At the level of the navicular tuberosity insertion of the tibialis posterior tendon, a posterior band projects towards the sustentaculum tali connecting to the soft tissue covering and surrounding the sustentaculum tali. The frequency of sustentaculum tali insertion was found to be 93.10 % of the sample. There was no difference between left and right feet. There was no significant difference between sexes or population groups, and no correlation with age.

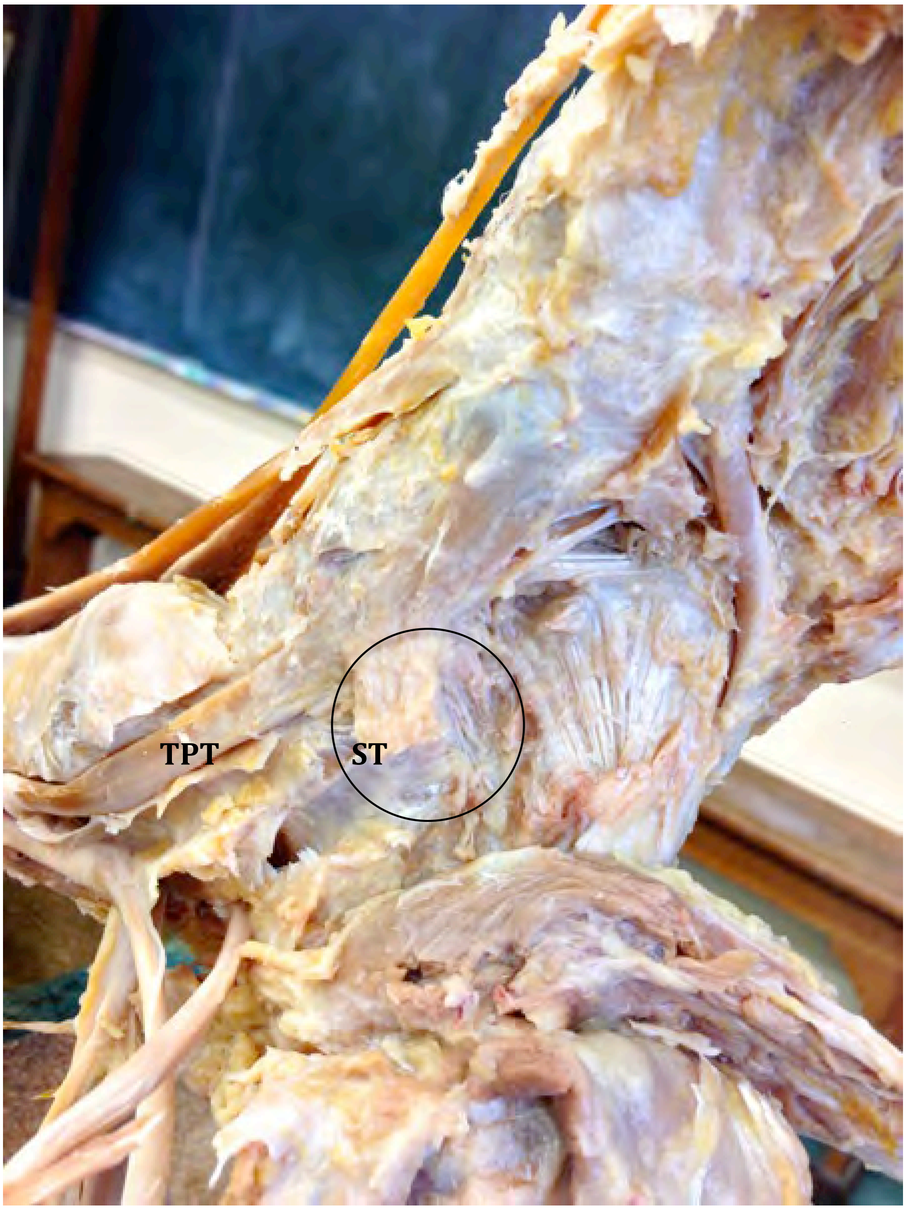

Figure 13 Thick connection (circled) from posterior band of TPT to ST.

Abductor hallucis

At the level of the navicular tuberosity insertion of the tibialis posterior tendon, a distinct slip connecting tibialis posterior tendon to abductor hallucis was present in 44.83 % of cadavers. The slip was always very small, and occurred in slightly different locations along the muscle belly of abductor hallucis. There was no difference between left and right feet. There was no correlation with age, sex, or population group.

Figure 14 This sample had connections (circled) to PL, LPL, as well as AH (reflected). The fibres to AH were typically to the deep surface of the muscle around the level of the navicular tuberosity insertion.

Flexor hallucis brevis

Projecting anteriorly from the navicular tuberosity insertion of the tibialis posterior tendon, the anterior portion of tibialis posterior tendon had a distinct slip connecting to flexor hallucis brevis 22.41 % of the time. There was one sample where a flexor hallucis brevis insertion was present in the left foot but not the right foot. This difference in one cadaver is not statistically significant, and may be explained by dissection error. There was no significant difference in insertion frequency between sex, age, or population group. This insertion was very small, connecting the anterior tibialis posterior tendon to the deep surface of flexor hallucis brevis at any level between the navicular-medial cuneiform joint and the first metatarsal head.

Figure 15 Continuation of TPT (circled) from navicular insertion to the base of FHB (reflected) can be seen.

Fibularis longus

Of all the variable insertions reported, the slip connecting the tibialis posterior tendon with fibularis longus was the most well defined, largest, strongest, and most distinct. Unlike the slips connecting tibialis posterior tendon with flexor hallucis brevis and abductor hallucis, which connected to the muscle belly or fascial tissue between muscle layers, this was a continuation of both the fibularis longus tendon and the tibialis posterior tendon. This insertion varied greatly in size and strength, and was present in 58.62 % of feet, which is similar to what has been previously reported. There were two cadavers where the slip was present in the left foot and not the right, as well one cadaver where the slip was present in the right but not the left. Despite the statistical insignificance of this variation within the sample, the distinct differences between left and right were of interesting note. In all the samples, the slip is a distinct tendon emanating from the middle tibialis posterior tendon as well as the fibularis longus tendon, just before they both the base of the first metatarsal. The photograph below shows the triangular shaped structure created by the tibialis posterior tendon and fibularis longus tendons, and the slip connecting the two. Manually pulling on the tibialis posterior tendon, the fibularis longus tendon, and the slip connecting them indicated their strong and intimate connection, suggesting further importance to this variably present structure. There was no difference between age, sex, and population group.

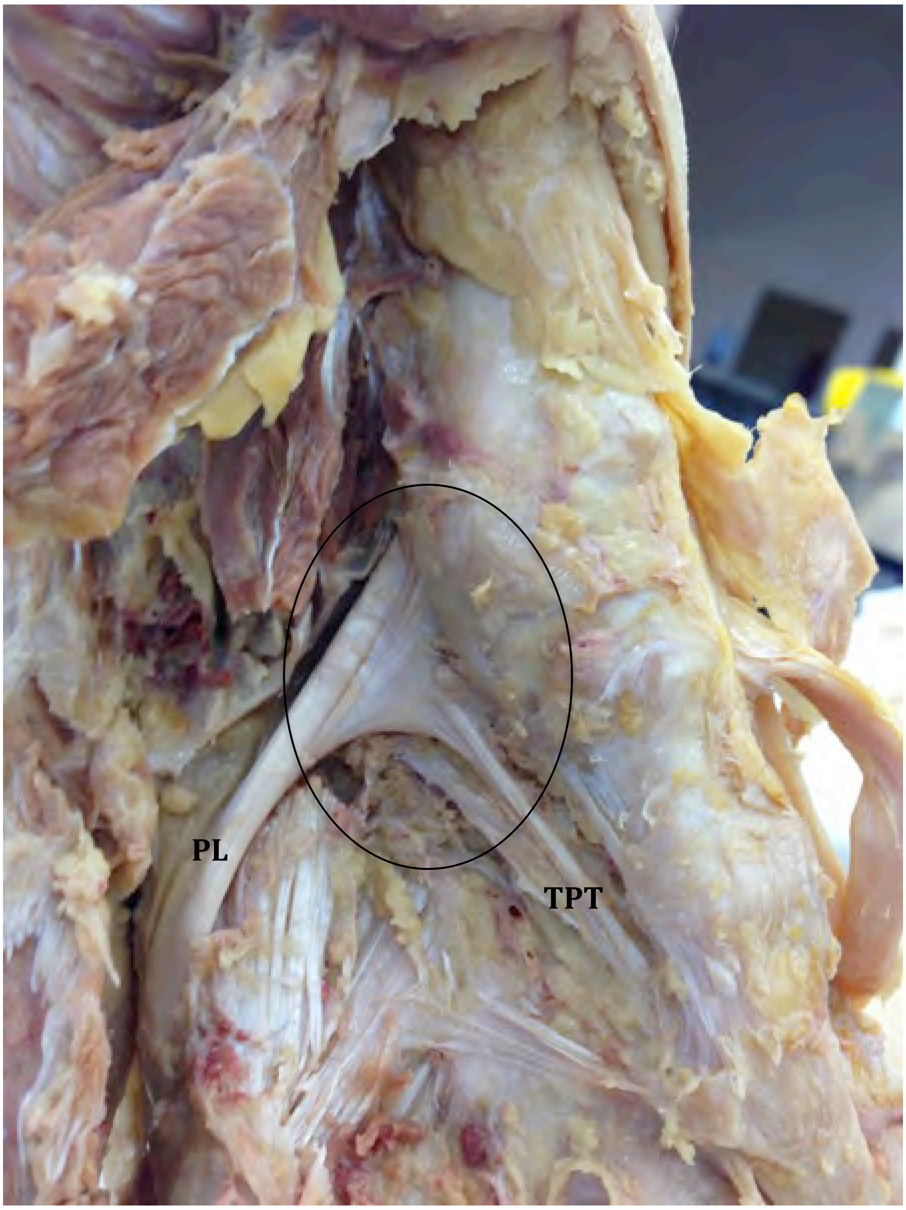

Figure 16 Strong connection (circled) between middle band of TPT and PL tendon near the base of the first metatarsal.

Spring ligament

At the level of the tibialis posterior tendon insertion at the navicular tuberosity, the posterior slip of tibialis posterior tendon inserted in to the sustentaculum tali, as well as the spring ligament. This insertion occurred in 17.24 % of feet. While the prevalence of the sustentaculum tali was quite high, a distinct slip to the similarly located spring ligament was not nearly as frequent.

There was no difference between left and right feet. The frequency of insertion was not significantly different between age, sex, and population group.

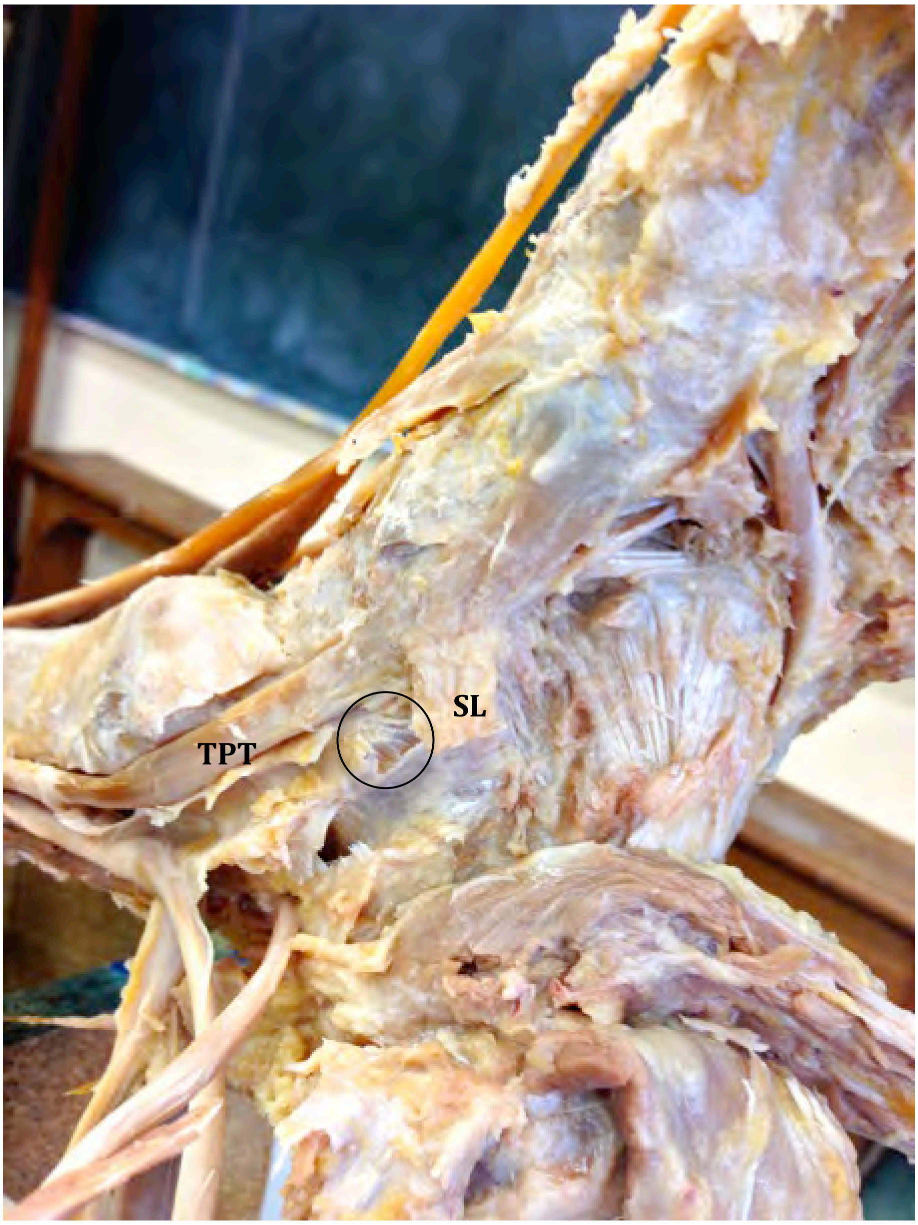

Figure 17 The connection (circled) between TPT, ST, and SL was often similar. The connection typically stopped at ST, but in this case it was continuous with the SL as well.

Long plantar ligament

A connection between tibialis posterior tendon and the long plantar ligament emanates from the middle slip of the tibialis posterior tendon, inserting in a fan shape to the long plantar ligament in 34.48 % of the sample. This slip was triangular, starting as a distinct slip from tibialis posterior tendon, and fanning out into several smaller slips as it inserted into long plantar ligament. The fibres of long plantar ligament and tibialis posterior tendon were perpendicular to each other. There was no difference between left and right feet. No correlation was shown between age, sex, and population group.

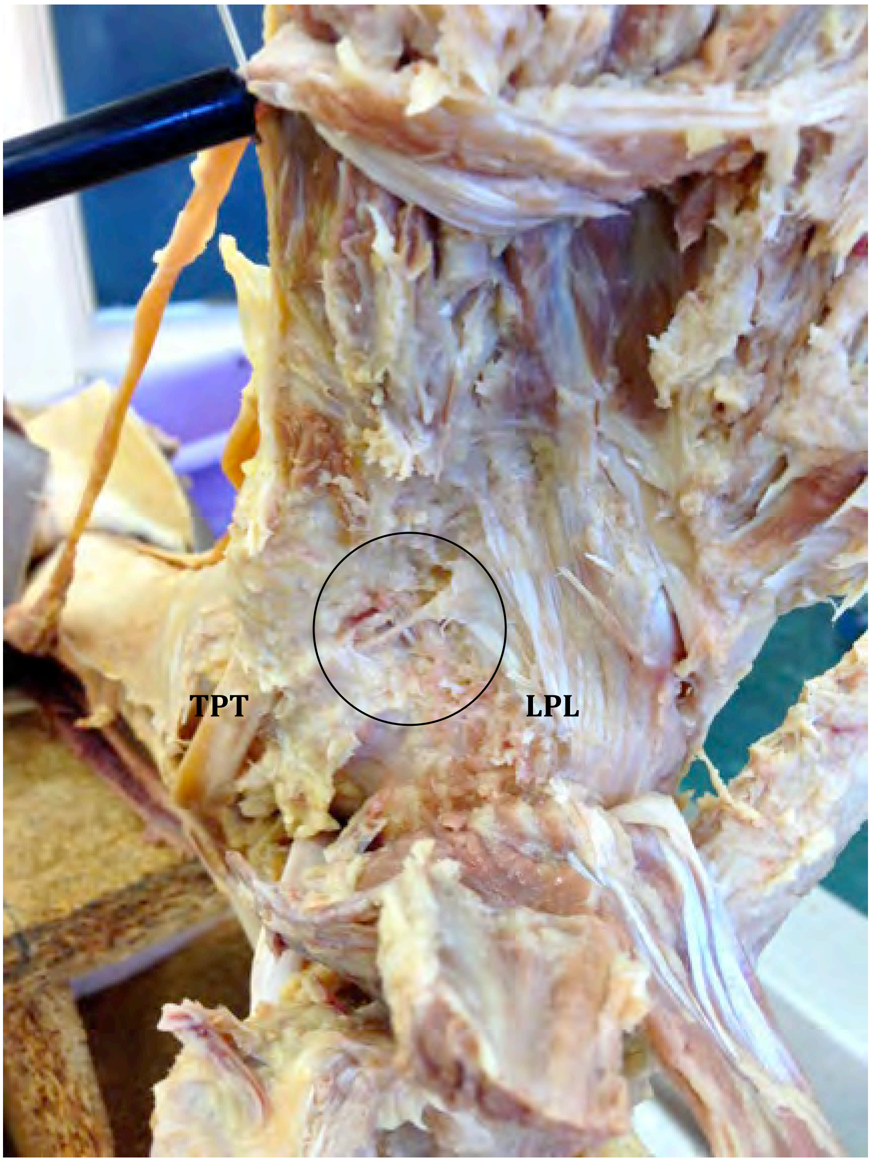

Figure 18 Small continuation (circled) of middle band of TPT to the LPL. The fibres of TPT and LPL were perpendicular but interwoven.

Connection	Overall Frequency (%)	Previously Reported (%)	Female Frequency (%)	Male Frequency (%)	Mixed-Race Frequency (%)	White Frequency (%)	Black Frequency (%)
ST	93.1	~100[13]	90.9	94.4	100	81.8	100
AH	44.8	45[13]	63.6	33.3	66.7	27.3	0.00
FHB	22.4	8%[13]	18.2	25.0	20.0	27.3	16.7
PL	58.6	36[13], 22[14]	63.6	55.6	66.7	40.9	83.3
SL	17.2	36[13]	27.3	11.1	20.0	18.2	0.00
LPL	34.5	--[15]	18.2	44.4	46.7	18.2	33.3

Table 2 Table showing observed and previously reported frequencies of variable insertions of TPT.

Cumulative number of variable insertions

As expected, the most common number of variable insertions within each cadaver was 3 (out of the 6 possible). Of the 58 feet dissected, 21 had three variable insertions. The cumulative number of insertions was a bell-shaped curve, with three and two insertions being the most common in the middle, and zero and six being the least common. When looking at the most common number of variable insertions, i.e. three, it is worth determining which insertions make up those three. Four combinations of insertion were observed, namely: ST-AH-PL, ST-AH-LPL, ST-AH-FHB, and ST-FHB-PL. The ST-AH-PL combination was present in 7 out of 21 the feet with three variable insertions (33.3%), and these three variable insertions constitute the most common variable insertions across the entire sample (93.1%, 44.8%, and 58.6%, respectively). The ST-AH-LPL combination was present in 6 out of 21 feet (28.6%) with three variable insertions (long plantar ligament has a 34.5% occurrence in individual feet across the whole sample. Sustentaculum tali, abductor hallucis, and long plantar ligament are the first, third, and fourth most common variable insertions,

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[13] Bloome et al., 2003

[14] Sarrafian, (1993)

[15] Although this connection has been noted, no studies focusing on its frequency have been performed.

respectively). The ST-AH-FHB combination was shown in 4 out of 21 (19.0%) of the feet with three variable insertions (flexor hallucis brevis occurs in 22.4% of the entire sample and is the fifth most common variable insertion). The final and least common combination within the three-variable insertion group, ST-FHB-PL, was present in 2 out of 21 (9.52%) of the feet. The variable insertion that is least common across the entire sample, spring ligament, was not present in any of the feet with three variable insertions. The spring ligament insertion was only present in feet that had four variable insertions or more. Conversely, the most common variable insertion, sustentaculum tali, was only absent in feet that had no variable insertions. The make up of the cumulative insertion groups directly follows the frequencies with which the individual insertions across the entire sample occur. Going from zero to six variable insertions, those that make up each group follow the individual frequencies (i.e. the one group only has sustentaculum tali, the two group most commonly has ST-PL, etc.).

Number of Insertions	**Frequency**	**Per cent (%)**	**Combinations**
0	4	6.90	--
1	6	10.3	ST (100 %)
2	15	25.9	ST-PL(46.7%), ST-LPL(26.7%), ST-AH(20%), ST-FHB(6.7%)
3	21	36.2	ST-AH-PL(33.3%), ST-AH-LPL(28.6%), ST-AH-FHB(19.0%), ST-FHB-PL(9.52%)
4	4	6.9	ST-AH-PL-LPL(50%), ST-PL-SL-LPL(50%)
5	6	10.3	ST-AH-FHB-PL-SL(66.7%), ST-AH-PL-SL-LPL(33.3%)
6	2	3.4	All (100%)

Table 3 Cumulative number of insertions frequency.

Arch measures

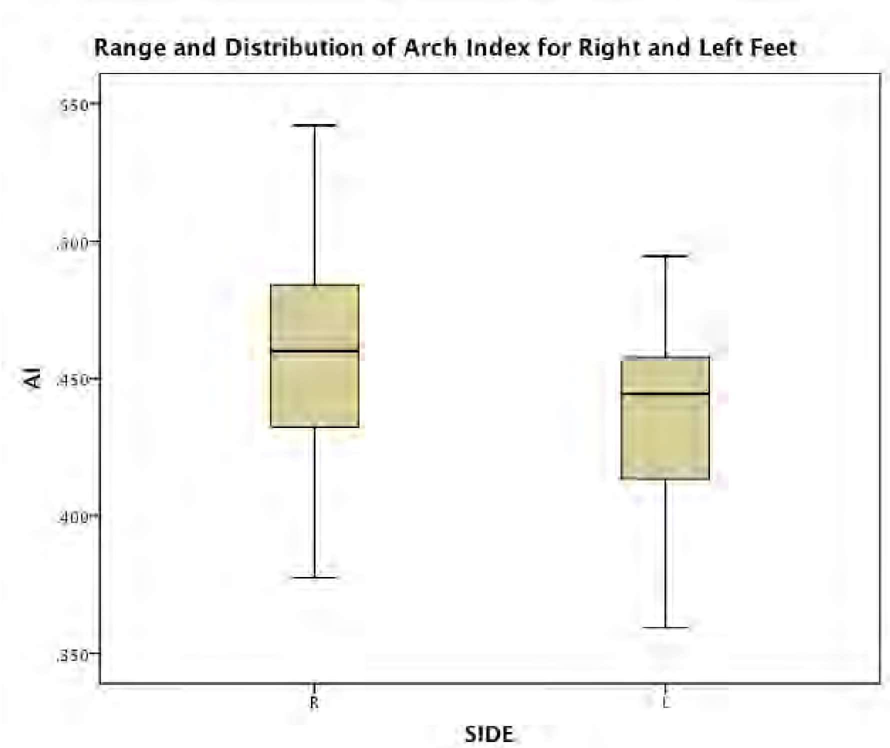
Arch index

The arch index measurements were normally distributed. The average arch index was 0.449 with a standard deviation of 0.040. The highest arch had an arch index of 0.542 while the lowest was 0.359.

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
AI	58	0.359	0.542	0.449	0.040
Valid N (list wise)	58				

Table 4 Descriptive statistics for AI within the sample.



Graph 1 Range and distribution of AI for left and right feet were similar.

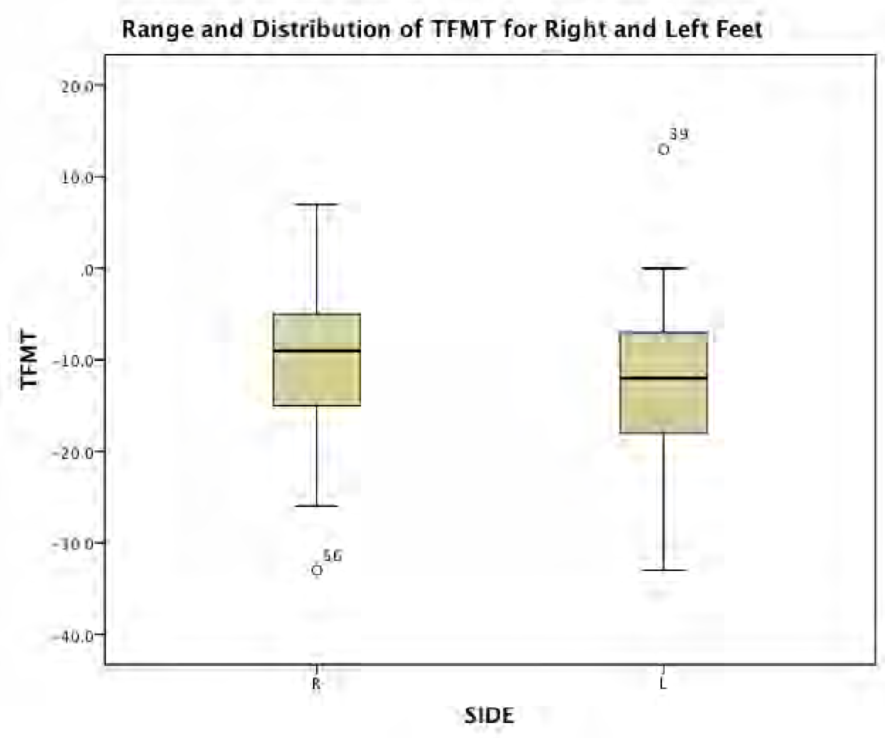
Talus-First Metatarsal angle

The talus-first metatarsal angle angle measures were normally distributed. The average angle was -11.2 degrees with a standard deviation of 9.14 degrees. The highest arch had a talus-first metatarsal angle of -33.0 degrees while the lowest was 13.0 degrees.

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
TFMT	58	-33.00	13.00	-11.19	9.143
Valid N (list wise)	58				

Table 5 Descriptive statistics for TFMT within the sample. Measurements are given in degrees. A negative angle indicates a higher arch, and vice versa.



Graph 2 Range and distribution of TFMT for left and right feet. Measurements were similar.

Relationships

General Linear Regression

AI	**Coef.**	**Robust Std. Error**	**t**	**P>|t| (0.05)**	**95% Confidence**	**Interval**
ST	-0.005	0.020	-0.148	0.883	-0.068	0.059
AH	0.003	0.021	0.125	0.901	-0.040	0.045
FHB	-0.018	0.021	-0.849	0.400	-0.061	0.025
PL	0.010	0.016	0.631	0.531	-0.021	0.040
SL	0.003	0.025	0.132	0.895	-0.048	0.055
LPL	-0.024	0.019	-1.283	0.206	-0.063	0.014
Side	0.024	0.008	3.122	**0.003**	0.008	0.039
Age	0.000	0.001	-0.180	0.858	-0.001	0.001
Sex	0.020	0.019	1.051	0.299	-0.018	0.058
Ethnicity	0.002	0.012	0.12	0.903	-0.24	0.027
Count	0.004	0.004	1.11	0.274	-0.003	0.012
_cons	0.390	0.036	10.83	0.000	0.316	0.464
TFMT	**Coef.**	**Robust Std. Error**	**t**	**P>|t| (0.05)**	**95% Confidence**	**Interval**
ST	12.66	6.357	1.991	**0.052**	-0.137	24.46
AH	0.566	4.228	0.134	0.894	-7.944	9.075
FHB	-2.757	4.360	-0.632	0.530	-11.53	6.018
PL	4.999	3.175	1.575	0.122	-1.391	11.39
SL	-4.658	5.166	-0.902	0.372	-15.06	5.740
LPL	-1.538	3.816	-0.403	0.689	-9.219	6.143
Side	2.405	1.690	1.424	0.161	-0.995	5.806
Age	-0.067	0.127	-0.525	0.602	-0.322	0.189
Sex	0.769	3.772	0.204	0.839	-6.824	8.361
Ethnicity	-0.508	2.349	-0.22	0.830	-5.319	4.303
Count	-0.421	1.016	-0.41	0.682	-2.501	1.660
_cons	9.776	8.623	1.13	0.267	-7.887	27.44

Table 6 General linear regression for AI and TFMT with all predictive variables. For AI, there is a statistically significant relationship with foot side. For TFMT, although not statistically significant, there is a weak relationship between TFMT and ST.

Pearson Correlations

AI	**AI**	**ST**	**AH**	**FHB**	**PL**	**SL**	**LPL**
Pearson Correlation	1	0.061	0.067	0.025	0.009	0.111	0.174
Sig. (2-tailed)		0.649	0.615	0.853	0.946	0.408	0.191
N	58	58	58	58	58	58	58
TFMT	**TFMT**	**ST**	**AH**	**FHB**	**PL**	**SL**	**LPL**
Pearson Correlation	1	**-0.216**	0.111	0.093	**-0.215**	0.105	0.111
Sig. (2-tailed)		0.104	0.408	0.486	0.106	0.432	0.406
N	58	58	58	58	58	58	58

Table 7 Pearson correlations for AI and TFMT with predictive variables. There is a weak negative relationship between TFMT and ST/FL.

The general linear regression for arch index and talus-first metatarsal angle with all predictive variables shows two relationships. For arch index, there is a statistically significant relationship with foot side. The coefficient of determination for this was determined to be 0.024, with a P-value of 0.003, representing a strong relationship. For talus-first metatarsal angle, there is a weak relationship between angle and the sustentaculum tali insertion (P-value of 0.052), though not statistically significant. The Pearson correlations for the same data show a weak relationship between talus-first metatarsal angle and both sustentaculum tali (coefficient of -0.216) and fibularis longus (-0.215) insertions.

Individual Insertions and MLA

General linear regression analysis showed that there are not any statistically significant relationships between any of the insertion predictor variables (sustentaculum tali, abductor hallucis, flexor hallucis brevis, fibularis longus, spring ligament, and long plantar ligament) and the dependent variables of arch index and talus-first metatarsal angle. The strongest relationship was between talus-first metatarsal angle and sustentaculum tali, where the absence of the sustentaculum tali insertion results in a slightly higher talus-first metatarsal angle (lower arch), but the $P > |t| = 0.052$ is not statistically significant (see table 6). Using Pearson correlation analysis, it was shown that there is a weak negative relationship between talus-first metatarsal angle and the sustentaculum tali insertion, and also the fibularis longus insertion, with values of -0.216 and -0.215, respectively (see table 7). All other correlations using Pearson correlation analysis were negligible.

Cumulative Insertions and MLA

There was not a statistically significant relationship between the cumulative number of insertions and arch index or talus-first metatarsal angle (See “count” in table 6).

Age

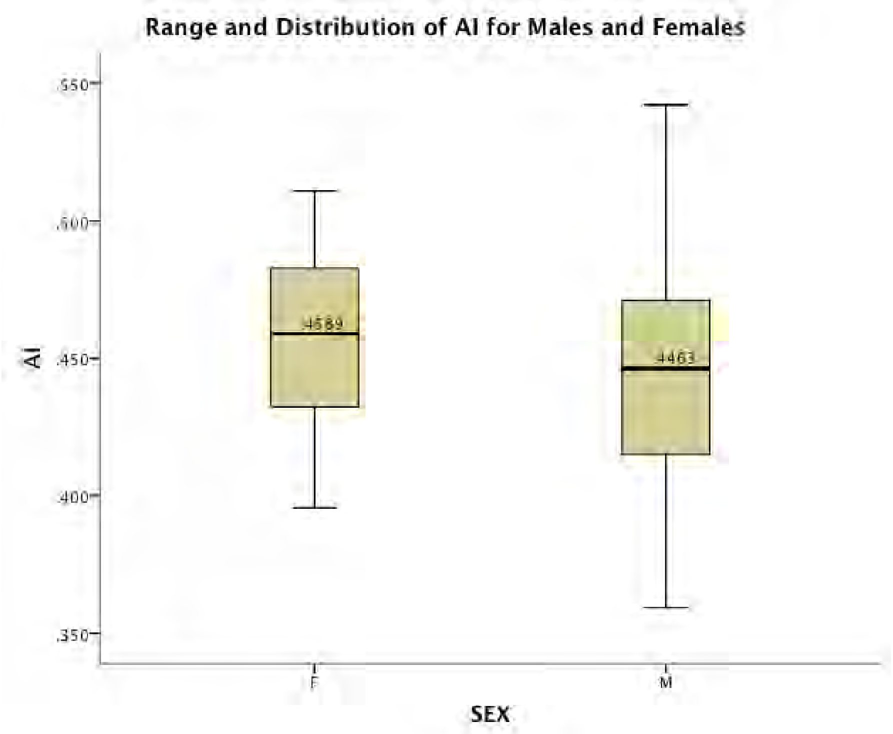
The age data were normally distributed. There were no statistically significant relationships between arch index and age, or talus-first metatarsal angle and age.

Graph 3 Scatter plot and line of best fit indicating the nearly constant AI measurement across all ages.

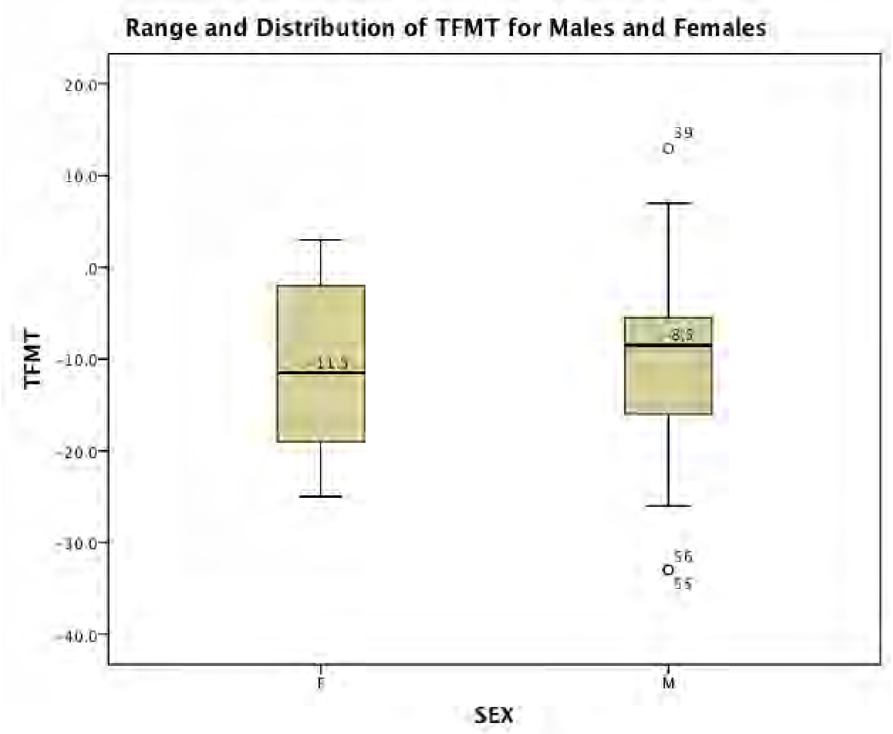
Graph 4 Scatter plot and line of best fit indicating the slightly negative relationship between age and TFMT.

Sex

There was not a statistically significant difference between the sexes in terms of frequency of individual insertions, the cumulative number of insertions, arch index measures (P > |t| = 0.299), and talus-first metatarsal angle measures (P > |t| = 0.839). The range and distribution for arch index and talus-first metatarsal angle measures were similar for both males and females. The average arch index for females was 0.459, while the mean arch index was 0.446 for males. Females had a mean talus-first metatarsal angle of -11.5 degrees while males had an average talus-first metatarsal angle of -8.5 degrees.



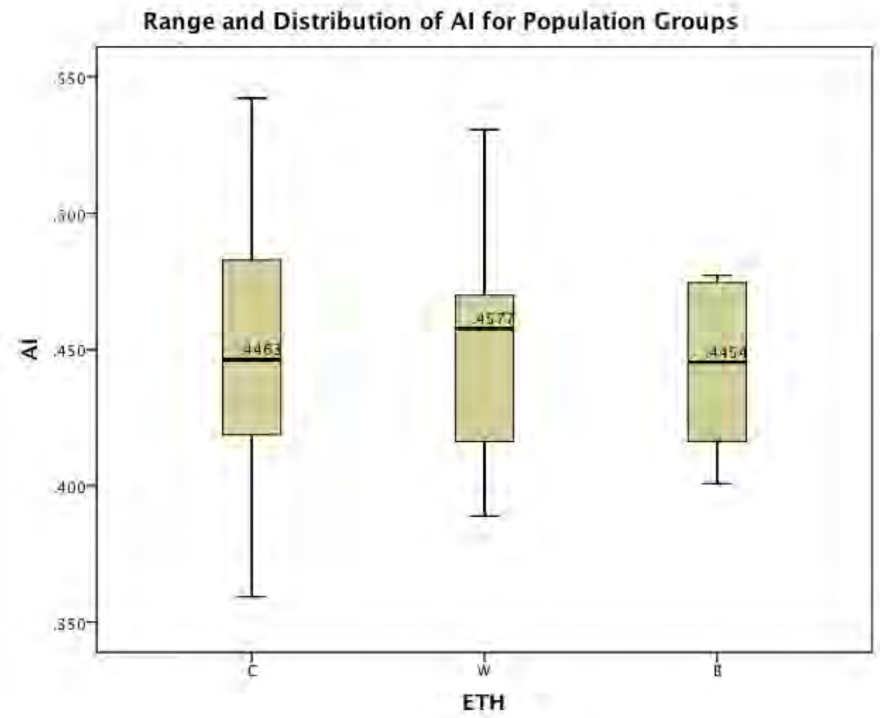
Graph 5 The range and distribution of AI for both males (range of 0.183) and females (range of 0.103) were similar.



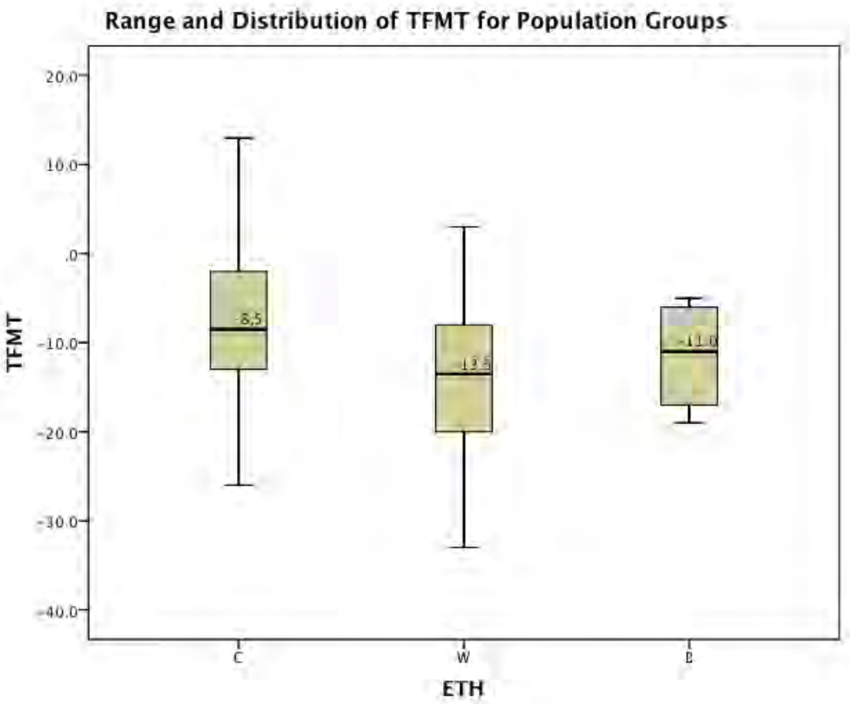
Graph 6 The range and distribution of TFMT for females (22 degrees) and males (20 degrees) were similar.

Population group

There was not a statistically significant difference between population groups regarding the frequency of individual insertions or the cumulative number of insertions. There were no statistically significant differences in arch index (P > |t| = 0.903) or TFMT (P > |t| = 0.830) between population groups. The mean arch index for mixed race individuals was 0.446, for Whites it was 0.458, and for Black individuals it was 0.445. Mixed race individuals had a talus-first metatarsal angle angle of -8.5 degrees, Whites had an angle of -13.5 degrees, and -11.0 for Black individuals. Additionally, the range and distribution within each population group was similar for both arch index and talus-first metatarsal angle measures.



Graph 7 The range and distribution of AI for each population group were similar. 0.183 for coloured, 0.142 for white, and 0.076 for black.



Graph 8 The range and distribution of TFMT for each population group were similar.

Side

Linear regression analysis has shown that right and left side within an individual sample are not independent of one another. Additionally, the linear regression for arch index has shown that there is a statistically significant relationship with foot side (P > |t| = 0.003). See table 6.

Discussion

Variable insertions

The highly variable insertions of tibialis posterior tendon were successfully documented and the frequencies of their existence determined within this South African population. The frequencies were relatively in line with what has been previously reported, and the larger sample size of this study adds to the scientific knowledge regarding the existence of these variations. As one might expect, the most common number of total variable insertions was three out of a possible six. Furthermore, those individuals that exhibited one variable insertion only had the most common insertion (sustentaculum tali), and this trend continued for each group (zero to six total variable insertions). There were four cases where an insertion was found in one foot but not the other in an individual. One of these cases, where the flexor hallucis brevis insertion was found in the left but not the right, may be explained by dissector error. This insertion was very small and could have been unintentionally removed or overlooked during the dissecting process. The other three cases all involved the TPT-PL connection, and they were definitely different between sides. This asymmetry with the connection may indicate the developmental nature of this variation. Finally, it is likely that the complexity and high degree of variability in the insertions of tibialis posterior tendon are a result of the relatively recent evolutionary changes that have taken place, and the increasingly important role of tibialis posterior due to the development of the longitudinal arch and bipedal locomotion has resulted in the differences between individuals. Further analysis of the fossil record, as well as biomechanical models could help to reinforce these notions.

Insertions and the medial longitudinal arch

The statistical analysis between the arch measurements and the presence or absence of variable insertions (as well as the accumulation of multiple insertions) has shown that insertions are not a predictor of arch height. Despite this, it can only be said that this is true for the static condition. Although insertions may have no effect on the actual structure of the arch as defined by the arch index and talus-first metatarsal angle, the biomechanics may be affected, and therefore further studies are needed. Although not statistically significant, the relatively strong relationship between the absence of sustentaculum tali and the talus-first metatarsal angle in the sample is of note. It is logical to assume that the absence of the sustentaculum tali insertion may result in a larger talus-first metatarsal angle (which indicates a lower arch) because of its location. The insertion from tibialis posterior tendon to sustentaculum tali is on the posterior band, travelling posteriorly from the navicular insertion to the sustentaculum tali. This insertion may elevate the anterior part of the talus, resulting in the talus being more in line with the first metatarsal, thus making the arch higher. The sustentaculum tali insertion was by far the most common (93.1%), and so a larger sample of feet without this insertion is needed in order to conclusively define the relationship between the presence and absence of the sustentaculum tali insertion and the structure of the medial longitudinal arch. The Pearson correlation analysis did in fact show a weakly negative relationship between sustentaculum tali and talus-first metatarsal angle (-0.216), meaning that the absence of sustentaculum tali did result in a larger talus-first metatarsal angle measurement (a lower arch). The connection between tibialis posterior tendon and the tendon of fibularis longus was interesting and is in need of further study. As previously mentioned, this connection had no effect on the medial longitudinal arch as shown by linear regression, however it was by far the strongest and most complete connection observed within the sample. Pearson correlation analysis did show a weakly negative correlation between talus-first metatarsal angle and fibularis longus (-0.215). The frequency of this connection has been reported previously, and my results indicate that it may be more prevalent than originally shown (58.6 % of my sample). It has been hypothesised, although not tested, that this connection may support the Lisfranc Joint Complex, and so further experiments and biomechanical studies are needed in order to deduce the structural or biomechanical significance of this common variation in tibialis posterior tendon insertion. Although this insertion does not have an impact on the static structure of the arch, there is undoubtedly some significance, perhaps biomechanical, to its existence. Foot side was shown to be an effective predictor of arch index ($p = 0.003$), and arch index measures between left and right feet on individuals were not independent of one another. One would not expect the arches in one individual to differ greatly between left and right feet. It is interesting to point out that 55% of the sample had a larger right foot arch index, which is similar to the percentage of the population that is right footed (Oldfield, 1971). Although further study is needed, it may be that, by favouring one foot over the other, the muscles in that foot become slightly hypertrophied in comparison to the other foot. This would be reflected by the arch index measurements, as it includes the intrinsic foot muscles. A study could be performed where arch index measurements are taken on left and right feet of living individuals, and their preferred foot documented. This relationship between arch index and foot side may also suggest that arch height could be improved, and thus related injuries reduced, by specific exercises isolating tibialis posterior and other important muscles related to pronation and gait. Just as previous studies have shown that taping the arch decreases tibialis posterior activity, exercises could be used to strengthen tibialis posterior, thus reducing the risk of injuries associated with an ill-functioning tibialis posterior as well as a low arch. My findings that the favoured foot may also have a higher arch shows that preferential use of muscles may improve arch structure. Finally, my arch measures were taken on non-weight bearing cadavers. Despite this limitation, I believe on the basis of previous arch deformations studies (see Razeghi et al., 2002) that my non-weight bearing data can be extrapolated to living, weight bearing subjects, because a “high arch” is usually still high whether weight bearing or not. More complex biomechanical analysis that accounts for the connections between tibialis posterior tendon and these other intrinsic foot muscles/tendons is needed. Current biomechanical models ignore intrinsic foot muscles altogether, as the complexity outpaces the information it could provide. I am proposing that biomechanical analyses should take into account not only intrinsic foot muscles, but also the fact that tibialis posterior tendon, which is the main extrinsic medial longitudinal arch supporter, is connected to several intrinsic soft tissue structures. Although I did not show a correlation between arch structure and variable tibialis posterior tendon insertions, the complex and variable insertions of tibialis posterior tendon indicate its relatively recent evolutionary development, as well as its complex role in supporting the medial longitudinal arch.

Critique and reflections

The overall sample size used in this study was sufficient to produce valid results and is an improvement on the sample sizes of previous studies. Within this sample Black individuals were relatively underrepresented, however I hypothesised that population group would not play a role in the frequency of insertions or arch measurements. The data collected in this study is accurate based on its statistically normal distribution and the findings are in agreement with previous reports. All of the arch index measurements that were physically taken on the cadavers were repeated once to ensure accuracy. The talus-first metatarsal angle angles were also measured twice. The data can be effectively utilized for the various statistical analyses required for the hypotheses I set out to test, as well as a database for future research projects. I find it surprising that the statistical analyses did not show strong relationships between the arch measures and the variable insertions. Being that tibialis posterior is the main extrinsic supporter of the medial longitudinal arch, one might expect that variations in its insertion would have some impact on the anatomy of the arch. One limitation of this study is that the study was not performed on living individuals, and so post-mortem changes would have occurred. Another limitation is that it was performed on embalmed cadaveric material, which may have undergone changes from the natural state. Finally, the study is limited by the fact that the samples that were measured were static and non-weight bearing. If it were possible to identify these variable insertions in living subjects using imaging technology that is currently available or may be available in the future, and then perform various tests, both static and mobile, some relationships may be shown. Despite these limitations, the findings improve our understanding of the insertion anatomy of tibialis posterior tendon and its relationship to the medial longitudinal arch.

A future study could account for these limitations by taking images on living subjects that have bequeathed their bodies to a medical school. Various tests and measurements relating to the medial longitudinal arch in both static and mobile scenarios could be taken prior to death. The images and test results would then be used to look for correlations with the findings from post-mortem dissections and measurements. This type of study would be long term as we would have no way of knowing when the individuals who have donated their bodies would pass, and is therefore inappropriate for a study at this level.

Upon examination of the frequencies presented in table 2, there appear to be rather significant differences in individual insertion frequencies between sexes and population groups. Most notably within the frequencies reported for sex was the abductor hallucis insertion, where males have 33% occurrence while females have 63.6% occurrence. This difference from a minority of the male group to a majority of the female group is of note, despite statistical analyses showing no significant relationships between sex and insertions. Similar trends are apparent in the population group frequencies, where the very common sustentaculum tali insertion (93.1% overall) is only absent in White individuals. The frequency of AH insertion is much lower in White and Black individuals than it is in Mixed-Race individuals, where in fact both abductor hallucis and spring ligament insertions are completely absent in Black individuals. This may be explained by the relative underrepresentation of Black individuals, rather than it being that population group is related to insertion frequency.

The reporting on the variable insertions of tibialis posterior tendon, specifically in reference to sex, population group, age, and foot side, is extremely beneficial to our understanding of this important and oft injured muscle, and the variations have not been studied extensively. This study is the first attempt to attribute some structural significance to the variations, and it also has the largest sample size to date for the reporting of the insertion frequencies on cadavers. As previously mentioned, knowing that the medial longitudinal arch and tibialis posterior play such an important role in gait, it is essential that biomechanical models start to include the more complex motions of the ankle joint, rather than simply plantar and dorsiflexion as is the current standard. Additionally, more complex biomechanical models that include these findings that the tibialis posterior tendon has a complex and variable insertion anatomy, with many connections to other intrinsic muscles in the foot, may illuminate the functional significance of the variations.

The final source of error could be during the dissection of the specimens. Although great care was taken in locating the variable insertions, it is possible that some were overlooked or inadvertently removed prior to identification. Many of the insertions were very small, and also not in the same location for every sample, leaving a certain room for error. All observed frequencies in my study were similar or higher than what has been previously reported, indicating the accuracy of my dissections.

Finally, the connection between tibialis posterior tendon and the tendon of fibularis longus was extremely interesting. It is surprising that this slip is so often omitted from the literature, as it was the easiest to identify, the strongest, and the largest connection. It did have a weakly negative correlation to the talus-first metatarsal angle measures, however due to its location it may have some other structural significance (perhaps as a Lisfranc Joint Complex supporter, as previously mentioned). Additionally, I found this connection in a greater frequency of the population than previously reported. A future research project could focus solely on the connection between tibialis posterior tendon and fibularis longus in an attempt to delineate its functional significance.

Conclusion

My hypothesis that the absence of specific variable insertions of tibialis posterior tendon will result in a lower arch was shown to be incorrect. The presence or absence of any one insertion did not have an impact on the height of the arch, as shown by the arch index and talus-first metatarsal angle measurements taken. Likewise, my hypothesis that the accumulation of multiple variable insertions would result in a higher arch was also shown to be incorrect. Of the six possible variable insertions that were documented, the majority of the sample had three, and having less than or more than three did not have a statistically significant effect on the arch index or talus-first metatarsal angle measurements. There was a slight negative trend between age and talus-first metatarsal angle, as predicted, although age is not an effective predictor of arch index or talus-first metatarsal angle. The knowledge regarding the frequencies of variable insertions of tibialis posterior tendon was added to, specifically in a South African population, thus deepening our scientific understanding of tibialis posterior and its complex insertion anatomy. Finally, the frequencies of variable insertions were shown not to differ between, sexes and population groups, which has not been reported previously. There were four cases where an insertion was present in one foot but not the other on the same cadaver. The arch height as shown by arch index was shown to be dependent on foot side, and left and right feet are not independent of one another.

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