A Paleopathological Analysis to Identify Possible Adult Flexible Pes Planus from Pedal Bones

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ABSTRACT

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The medial longitudinal arches developed during the evolution of bipedalism. These arches have biomechanically significant tasks during propulsion and impact. High arches also have a history of admiration. However, a large percent of the population worldwide suffer from depressed longitudinal arches, a deformity called pes planus. The deformity is under lots of debate medically and underrepresented archaeologically and paleopathologically.

This study focuses on diagnosing pes planus from bones. There are multiple methods for medically diagnosing the deformity on living individuals, but only a handful of studies purely concentrate on the paleopathological side. For this study, the tali, naviculars, calcanei and tibiae of 32 individuals from the University of Helsinki human remains collection were measured and pictured. Angle measurements between two bones were calculated from the pictures and they were compared with each other and with the measurements of the bones to show correlations.

The results did not offer a simple method for diagnosing the deformity. What the research offers however, is more knowledge about the positions of bones affected by pes planus and changes in them. The results indicate that the width of the calcaneus has more influence on the medial longitudinal arch collapse than previously argued. Also, the angular shape of the talus head on the transverse plane correlated with some of the angles used in diagnosing pes planus clinically.

Keywords: *pes planus, flatfoot deformity, medial longitudinal arch, paleopathology, osteoarchaeology, University of Helsinki human remains collection*

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1. INTRODUCTION

There is a lot of controversy about pedal health when it comes to prevention, diagnosis, and treatment of certain deformities. Having flat feet is, by some, considered a flaw that needs (in some cases) to be fixed through surgery. Others consider depressed arches to be within the normal variation. Staheli (1999: 94) even suggested that the reason flat-footedness is seen as a disorder might be due to cultural values of beautiful, high, aristocratic arches. Then there is the group of people between these two extremes, who believe in correcting flat feet by exercise and by training the small muscles of the feet. They believe that trained muscles will correct pedal posture while walking and running. The topic is widely discussed currently and the debate is in need of a historical perspective.

I chose this topic to come up with a way to know if people in the past suffered from flatfoot deformity. The research on the changes that comes from depressed arches and the causes behind them is important for our wellbeing. The studying of flatfoot deformity on previous generations would provide a possibility to compare it to the pedal health of modern people and thus to study the effect that footwear has had on our feet. This knowledge on how footwear, the cushioning and the support of them, affects our feet would also contribute to getting better suited footwear in the future. Ideal footwear that would do no harm to the developing feet of children and would protect our feet just enough from the elements without restricting the natural movement of the foot.

Additionally, by having more knowledge about the reasons behind this deformity and what kinds of changes it inflicts on our bones, we might be better equipped to cure it medically and to relieve its symptoms. Also, methods for recognizing pes planus could provide aid in forensic cases by offering more means for a positive identification of an unknown individual. The knowledge might as well give better insight into the development of the medial longitudinal arch during the evolution of bipedalism. By knowing more about the changes manifested in bones and the historical frequency of the deformity, it is also possible to take part on the discussion about the nature of the flatfoot deformity. Whether it is just a normal individual characteristic or a medical condition that needs fixing. In any case, the deformity is greatly under-represented in paleopathological literature, and there is a lot more to be known about it.

The group of people in the middle of the debate, who believe in exercise for their feet to feel better, often discuss topics like barefoot shoes, barefoot running as natural running, forefoot strike, and so on. They point out to the fact that going barefoot was natural for humans already thousands and tens of thousands of years ago. With the rising trend of fitness, “paleo diet”, going back to the roots, and trying to live healthy and pure, barefoot shoes are also getting more and more popular amongst a bigger crowd. It should be noted however, that barefoot running does not suit everyone. In certain conditions, feet simply need some cushioning against hard ground. Lieberman (2012: 64) has concluded that, more important than running with barefoot shoes, is the technique of running. No types of shoes or not wearing them at all can save feet from a harmful technique.

Staheli (1999: 96) studied the effects of simply going barefoot without any shoes at all. He notes that according to a survey, only 2% of adults who had been going barefoot as a child, suffered from pes planus later on. The percentage for adults who had worn shoes was as high as 13%. He assumes that barefoot walking makes the muscles of the feet stronger, so they provide better support for the arch.

Rao and Joseph (1992: 526, 527) reached into a similar conclusion. They found out that the prevalence of having pes planus was 8.6% among children who had worn shoes growing up and only 2.8% in children who walked barefoot. Rao and Joseph also found out that the critical age for the longitudinal arch to develop would be prior to six years. According to them, children under the age of six should walk and play barefoot as much as possible. This was also agreed by Sachithanandam and Joseph (1995: 255). Additionally, they noted that prolonged weight bearing cannot be kept as a precursor to pes planus. Therefore, the cause for pes planus cannot be for instance continuously working upright.

The human body has also evolved to run with a forefoot strike. Modern highly cushioned and supportive running shoes have only been used since the 1970s. They give people the option of running with a heel strike, which would otherwise hurt them. Thus, cushioned shoes make it easier to run with bad technique, while the body does not give you a negative feedback. In the past, pain in the feet told a person if they were running wrong. Additionally, they also lived more active lifestyles and had to attend physical chores rather than sitting in front of computers eight hours a day. Therefore, my hypothesis is that when people did not use modern supported and cushioned shoes growing up and while running, their pedal health was generally better. So, can flatfoot deformity be referred to as mostly a modern condition? Or could it be an inherited characteristic?

There are some changes in the bones that have been linked to pes planus. Darton (2007: 287) notes the existence of eversion facets on tali due to the constant contact between the talus posterior articular surface and the edge of the sinus tarsi. The whole orientation of talus might also shift so that the talar head faces more inferiorly (Louie *et al.* 2014: 964). This would show in pictures mimicking radiographs taken to diagnose pes planus. Additionally, Van Boerum and Sangeorzan (2003: 423) detail that calcaneus tends to subluxate posteriorly due to a lowered medial longitudinal arch. The changes in these bones could also affect the bones around them, and the relationships between bones.

The aim of this research is to try and find changes caused by pes planus that would manifest on bones or in the relationships between them. The analyses would express non-weight bearing markers, such as independent morphological changes in the bones. They would also present some weight bearing markers, such as talocalcaneal angle differences caused by subluxation. However, obviously more weight bearing markers than the ones used in this study, can only be observed with an intact foot and applied weight.

Knowledge about these changes could offer an additional method for diagnosing flat foot from bones alone, with a primary focus on using the measurements of the angles between two bones. What if it would be possible to define the positions of the bones, take pictures of them and process the angles from the pictures using a computer program? The angle values would then be compared to each other and the correlations analyzed. Additional markers as eversion facets, calcaneus in valgus, the width of the calcaneus, and a more angular talar head on the transverse plane are also used to aid the diagnosis.

2. BACKGROUND

2.1 Evolution

Our hominin lineage has evolved from arboreal apes. Ponnapula (2012: 319) has noted that we are the only species of obligate bipeds out of all the extant primates. She adds that there is a locking mechanism that happens in the midtarsal joint to provide a rigid structure for push-off. Knowing how and why these characteristics evolved gives us an insight into how our feet are supposed to work, and what kind of effect deformities might have on that.

The reasons behind the evolution of bipedalism are highly debated. There are many hypotheses for it ranging from freeing hands to carry food to picking fruit from the trees (Ko 2015, 930, 932). Also the need to see further in open savannah or benefit from standing upright for thermoregulation have been suggested (Ko 2015: 930, 932). Additionally, one explanation is that hominins adopted bipedalism to inhabit marine wetlands for new food resources (Ellis 1993: 210). Probably there was no single reason behind it but developing a bipedal way of moving was due to a combination of multiple reasons.

Bipedalism is the best trait to distinguish human lineage (Soluri & Agarwal 2016: 360). As stated by Soluri and Agarwal (2016: 361), our ancestors have been obligate bipeds[1] probably since *Homo habilis* and habitual bipeds from very early on. They note that many primates practice occasional bipedalism[2], but already the australopithecines and even the pre-australopithecines were great examples of habitual bipeds[3].

The bodies of our ancestors needed to adapt to walking with two feet. Soluri and Agarwal (2016: 362–63) explain that there had to be several adaptations to morphology for carrying the whole body weight with only two feet. They add that, hominins did not need grasping feet anymore, but pushing off ability and balance. Therefore, our toes got shorter than before, and the hallux is adducted and more robust than the other toes (Soluri & Agarwal 2016: 365).

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[1] Obligate bipedalism: primary way of locomotion, no other reasonable options (Soluri & Agarwal 2016: 361).

[2] Occasional bipedalism: bipedalism is practiced under some circumstances, only occasionally (Soluri & Agarwal 2016: 361).

[3] Habitual bipedalism: bipedalism is used quite equally with another way of locomotion (Soluri & Agarwal 2016: 361).

Tardieu (2010: 181) notes that the change for opposable hallux not to form was probably the first for terrestrial adapted foot to develop. According to Lewis (1980: 296), there was also a re-orientation in the subtalar axis which aids in bipedal locomotion by directing the center of gravity. He notes that the center of gravity first deviates to the supporting side and after that, back towards the mid-line. In humans, pelvis is depressed on the side of swing phase, while in the chimpanzee, it is elevated caused by a substantial pelvic sway and tilt (Lewis 1980: 296). However, the most important notion on morphological changes for this study is the development of a longitudinal arch to assist in shock absorption and creating energy for push off (Soluri & Agarwal 2016: 365).

When exactly did these traits develop, is still questionable. Harcourt-Smith and Aiello (2004: 412–13) raise a question whether bipedalism even developed from a single origin. According to them, there could have been different modes of bipedalism on different taxa in different parts of Africa at a similar point of time. They also state that, multiple hominins had both human-like and mosaic bones in their ankles and feet. However, these varied a lot between the hominins. *A. africanus* (Stw 573) for example had an unopposable or intermediate hallux, a mosaic navicular, and an ape-like talus, compared to *A. afarensis* that had an unopposable hallux, and a human-like talus (Harcourt-Smith & Aiello 2004: 411). This shows that there were similarities, but also differences in the ways that bipedalism evolved and appeared.

2.2 Research Background

The field that studies disease in ancient populations from skeletal remains and soft tissue if preserved, is called paleopathology or palaeopathology (T. D. White & Folkens 2005: 309). White and Folkens (2005: 310–11) as well as Waldron (2009: 1) explain that paleopathology is restricted to the state of the remains and the diseases that are manifested on bones. The changes that can be seen on bones are a result of disorders during growth or imbalance in bone resorption caused by multiple reasons (T. D. White & Folkens 2005: 309). The reasons for imbalance as listed by White and Folkens include soft tissue inflammations and infectious diseases, mechanical stress, tumors and changes in the nutrition, metabolism, or hormones. However, Waldron (2009: 2) notes that paleopathologists do not have any universal system for diagnosing, which causes problems in comparing researches.

White and colleagues (2012: 430) state that paleopathological examination consists of two stages. First and most important, the pathological indicators should be described, and after that the diagnosis is made if possible. White and Folkens (2005: 310) add that the diagnosis is usually made based on radiology and gross appearance, and this causes lack of precision that can be seen as inter and intra observer errors.

While modern flat foot, a deformity also known as pes planus, is well researched and published, historical medical literature of the condition is rare (Wokaunn, Ferenčić, and Mikolaučić 2013: 1873). Flatfoot deformity is poorly noted in paleopathological literature, while the more easily detectible clubfoot is widely researched (Darton 2007: 290). However, Wokaunn and colleagues (2013: 1873) state that pes planus has been diagnosed from an individual who lived as early as in the first century AD. This is considered to be one of the oldest indications of pes planus known, they add. The research consisted of analyzing an engraved footprint that had implications of belonging to an individual suffering from flatfoot deformity. However, the research was only based on an engraving, which cannot be considered as reliable as diagnosing from bones.

Staheli (1999: 94) describes that traditionally low, fallen arches were considered a sign of poor health, while high arches were admired. He continues that in the 18th century children were being treated to prevent deformities in the adulthood. People believed that mechanical devices or posture control would correct their children´s feet, or that children should not stand because the upright position might lower their arches and cause bowlegs (Staheli 1999: 94). Staheli adds that, it was a common belief that feet could be molded with shoe inserts to create an arch while the child was still growing. He notes however, that according to today´s knowledge, most of these deformities tend to recuperate spontaneously.

Modern medicine has a wide knowledge of this common condition. According to Tenenbaum and colleagues (2013: 811), multiple pes planus studies have been done on the prevalence of pes planus on pediatric populations or older adults whose deformity is acquired. They state however, that these studies have given variable results and do not show the whole state to the deformity. A number of children tend to recover from fallen arches due to spontaneous correction (Tenenbaum *et al.* 2013: 815). Therefore, there is a problem with comparing those results with the studies on young adults with flexible pes planus.

There are some CT-scan studies on how flatfoot deformity might affect the bones. A study like this was conducted by Peeters and colleagues (2013: 284, 286), where they used 3D model bones from CT-scans. What they found out was that in flatfoot deformity talar head faces more proximally and the navicular articular facet is wider. Other talar dimensions however, were not different compared to controls. They add that the talar articular facet in navicular also faces more proximally.

Darton (2007: 287–88) conducted a study where they analyzed the modifications in the bones of seven medieval individuals from France. They reconstructed the bones into their natural positions and observed numerous osseous signs that would be an indication of structural changes in feet. Therefore, they were able to analyze and describe the bones and their orientations. Additionally, they also analyzed the condition of the articular parts of the bones. Darton explains that measurements where two bones would have been positioned and angles analyzed, were not made. He states that these measurements would not be reliable due to the difficulty of finding reproducible reference points. In this research, the angles are measured using strict guidelines. The bones are pictured consistently using a spirit level, and the angles are mostly drawn along the edges of the bones which makes them more uniform.

3. PES PLANUS

3.1 Morphology

The bones of a foot can be divided into two longitudinal columns (Kidd 1998: 79). Kidd explains that of tarsals, calcaneus and cuboid form the lateral column and talus, navicular, and three cuneiforms form the medial column. The first tarsal to begin ossifying is calcaneus (Burns 2013: 145). Burns details that, when a child is born, talus and calcaneus are the only ones present and the others will form over the next five years. Navicular is the last one to ossify.

According to Kidd (1998: 79), the tarsals can also be divided into anterior and posterior with the midtarsal joint. Kidd notes that the placement of the midtarsal joint is important in shock absorption and increasing the rigidity of the foot. It allows the arch to become shorter and higher for propulsion, and to elongate and diminish for shock absorption (Kidd 1998: 79).

Ponnapula (2012: 320) explains how talus had a big role in the transition into an obligate bipedal foot. She adds that, the talar neck angle showed interdependence with opposable hallux in fossil evidence. Talar neck angle reduction happens during ontogeny taking away first-ray divergence. Ability for midtarsal joint locking also evolves during ontogeny by increasing talar torsion (Ponnapula 2012: 320). Therefore, Ponnapula notes that primitive hominins probably lacked the ability to lock the midtarsal joint. She also states that there seems to be a higher tendency for developing flatfoot on those individuals that have decreased talar torsion angles and incompletely maturated talar necks.

3.2 The Flatfoot Deformity

After a transition into terrestrial environments, our feet did not need grasping abilities anymore. It was more important to carry our body weight, absorb shock caused by striding upright, and to lift body weight during stance (Saltzman *et al.* 1995: 45). As stated by Saltzman and colleagues, these advantages were provided by the development of a medial longitudinal arch on the foot. Lewis (1980: 276) states that in the development of the arched foot, an important factor was the tight position of hallucial tarsometatarsal joint

According to Saltzman and colleagues (1995: 45), it is not indifferent how high the arch is. They state that while the depressed longitudinal arch on pes planus can cause problems, an arch that is considered too high may also cause problems, especially activity-related ones. The arch stabilizing structures are ligaments, muscles, interlocking of tarsals, and plantar fascia (Huang *et al.* 1993: 353). Huan and colleagues (1993: 353,357) note that a change in these structures might result into a lowered arch. According to them, the most important stabilizer is the plantar fascia.

Tardieu (2010: 181) states that a longitudinal arch is already present in the newborns but hidden under a thicker plantar cushion. Gould and colleagues (1989: 244) had a different conclusion in their study on the development of children's arches. According to them, all toddles have pes planus until the arch develops. They examined how the arches of children would develop using different kinds of footwear. However, in my opinion they left the most effective way of developing a healthy arch out of the research, which is walking barefoot without any shoes at all. Staheli (1999: 96) backs up this claim by stating that, there is a lot smaller percentage of individuals with a flatfoot deformity among those who have walked barefoot while growing up than those who used any kinds of shoes.

The deformity called pes planus that manifests as fallen medial longitudinal arches, is a common condition worldwide. It is the most common pedal condition in the US, affecting all ages (Blackman *et al.* 2009: 1547). However, as there is considerable variation in cases of pes planus it cannot be referred to as a single disorder (E.J. Harris 2010: 2). The various causes behind flatfoot can be both congenital or acquired, and congenital is divided into a flexible flatfoot (physiologic) and a rigid flatfoot (pathologic) (Staheli 1999: 95; Van Boerum & Sangeorzan 2003: 419). McCormack and colleagues (2001: 15) explain that pes planus is a term describing the end point of processes that result in a depressed medial longitudinal arch. They also note that the deformity is comprehensive, while the changes can involve fore- mid- and hindfoot.

The research by Tenenbaum and colleagues (2013: 814) revealed some predisposing factors that have been linked to pes planus. They state that both overweight (BMI[4]) and short height are associated to all stages of flexible pes planus. However, the general problem in this statement is that BMI, which they used to measure overweight, does not separate fat and muscle (Romero-Corral *et al.* 2008: 963). Their study does not detail whether the factor of higher BMI is due to the lack of exercise, which usually means weaker muscles and higher weight, or is it considered a predisposing factor simply

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[4] Body mass index

because of the higher weight, without sorting out where the weight comes from. It has been researched that the accuracy of identifying overweight is especially limited on men and elderly in the intermediate ranges of BMI (Romero-Corral *et al.* 2008: 963–64). Tenenbaum and colleagues (2013: 814) also state that the deformity is more common among males. Additionally, they found a link between the prevalence of injuries and flexible pes planus in the study. However, even though women have lesser degrees of the deformity, they were more prone to injury.

Harris (2010: 1) notes that only the existence of a lowered medial longitudinal arch does not necessarily mean a disease or a pathological condition. There is wide variation in the height of arches, and even flatfeet are considered normal, if symptoms do not occur (Van Boerum & Sangeorzan 2003: 419). Therefore, in modern medicine, having flat feet is referred to as a medical condition only if it develops symptoms (E.J. Harris 2010: 1). The prevalence of symptomatic flatfoot was 57% according to the study by Pehlivan and colleagues (2009: 449). However, a definite connection between radiographs and symptoms has not been shown, and the symptoms can be either unilateral or bilateral.

Even without symptoms to occur, the deformity can still add the vulnerability of the posterior tibial tendon to inflammation and other changes (Park & Schon 2013: 104). The symptoms that a flexible pes planus may cause, include pain in the arch, heel and lateral parts of their feet (Lee *et al.* 2005: 86). As stated by Lee and colleagues (2005: 86), weight bearing activities, as sports, hiking and walking, might aggravate the symptoms. They add that the condition may also cause weakness and fatigue in the foot targeted.

Staheli (1999: 96) states that it is part of a normal development that the longitudinal arch has not formed yet on an infant. With time, arches tend to develop spontaneously, talus inclines, talometatarsal angles decline, and calcaneal pitch increases while the tendons tighten with the growing feet (Staheli 1999: 96). He notes that there is normal variability in the height of the arch across families and races. It might even be an inherited characteristic. However, if there is a congenital rigid deformity behind the depressed arch, the developmental causes of flatfoot in children usually consist of tarsal anomalies, such as tarsal coalition, extra bone called accessory navicular, and a congenital vertical talus (Van Boerum & Sangeorzan 2003: 419).

Even though rigid flatfoot is a congenital condition, it often develops symptoms only later on in life (Lee *et al.* 2005: 83; Park & Schon 2013: 104; Pedowitz & Kovatis 1995: 295). As stated by Pedowitz and Kovatis (1995: 295), the rigid deformity might be caused by tarsal coalition, tarsal anomalies that limit the movement of the joints, or a breakdown of the midfoot caused by a tight Achilles and increased stress on tarsal joints. Harris and Beath (1948: 626) have also detailed that most of the cases of rigid flatfoot with peroneal spasticity would be caused by a talocalcaneal bridge. These deformities are usually congenital and already observed on birth, unlike arthritic flat foot (Harris and Beath 1948, 629,630).

Medically the diagnosing of the deformity into rigid or flexible is evaluated by the range of motion during dynamic loading (Lee *et al.* 2005: 79). Due to the anomalies and morphological changes of the rigid flatfoot deformity manifested on bones, it is usually easier to detect than the physiological flexible flatfoot. Therefore, this study is concentrated on the clues that flexible flatfoot may leave on bones.

If the deformity expresses during adulthood, it is commonly called an Adult-acquired flatfoot deformity (AAFD) (Deland 2008: 399). McCormack and colleagues (2001: 15–16) state that AAFD is a multifactorial deformity and is therefore hard to diagnose and treat. The causes behind the fallen arch include: posterior tibial tendon (PTT) insufficiency, shortened lateral column, external rotation of hindfoot, abduction of the forefoot, midfoot laxity, talar subluxation, tight heel cord, trauma, Charcot's foot, arthritis, and neuromuscular imbalance (Blackman *et al.* 2009: 1547; Kitaoka *et al.* 1998: 447; Lee *et al.* 2005: 79; McCormack *et al.* 2001: 15).

Some researchers have even suggested that pathologic talocalcaneal or talonavicular joints might be the cause (Ponnapula 2012: 320). Lee and colleagues (2005: 79), and Blackman and colleagues (2009: 1547) note that pes planus is also linked with contracted or short Achilles muscle-tendon complex. Achilles tendon contracture may as well act as a contributing factor to the severity of flat foot deformity (Blackman *et al.* 2009: 1553). Pinney and Lin (2006: 67) explain that the medial longitudinal arch may depress to compensate a short Achilles tendon. They note that, a tight gastrocnemius muscle or a short Achilles tendon might restrain neutral dorsiflexion causing talonavicular joint subluxation. Persistent subluxation results in stress of the soft-tissue structures in the postero-medial foot (Pinney & Lin 2006: 67).

Four different stages of the adult acquired flatfoot deformity have been described (Deland 2008: 400; Johnson & Strom 1989: 196). Johnson and Strom list that the first stage does not include a deformity and the symptoms are often left unrecognized. Mild pain and tenderness might also exist, but the hindfoot-forefoot alignment is still normal. Stage two shows a developed flexible deformity with alignment changes (Deland 2008: 400). Deland (2008: 400–401) divides this stage further into IIa and IIb after the severity of the deformation. He explains that talonavicular coverage is less than 30% in IIa and over 30% in IIb. Deland continues with the third stage, where deformity is fixed, and hindfoot fusion exists. He further explains that in rigid, or fixed, deformity there is most regularly a triple arthrodesis. Rigid deformations are left out of this research. Stage four is the final stage, where deformity exists not only in the foot, but in the ankle joint as well (Deland 2008: 401). Deland details that this stage is also further divided into rigid and flexible.

According to the studies of Lee and colleagues (2005: 91), and Pedowitz and Kovatis (1995: 297), the most common cause for adult acquired flatfoot deformity is posterior tibial tendon (PTT) (figure 1) insufficiency. This tendon has a crucial place as a dynamic stabilizer of the foot (Park & Schon 2013: 104). It originates from two parts of the tibia, posterior fibula, and the intraosseous membrane and it attaches into the navicular, cuneiforms, cuboid, calcaneus and metatarsals (Pedowitz & Kovatis 1995: 297). As noted by Park and colleagues (2013: 104), PTT is usually considered an age-related or overuse condition, where the changes usually occur in the most biomechanically stressed areas of the tendon.

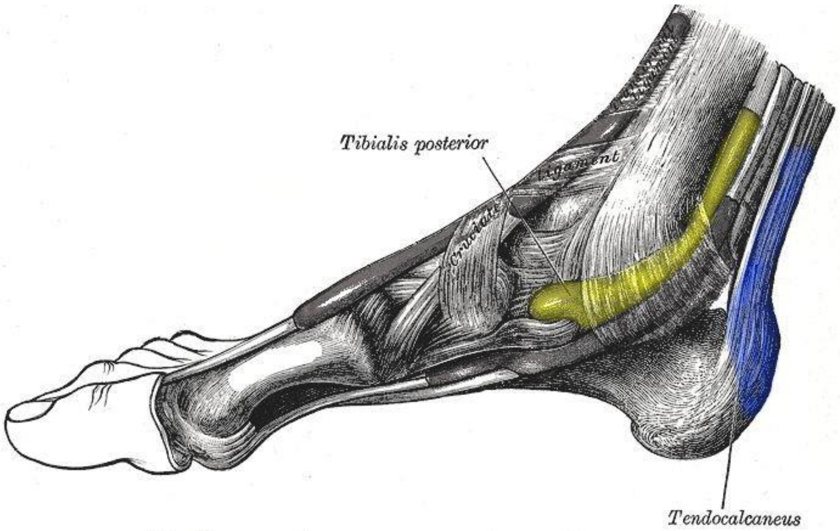

Figure 1. Medial view of the foot. Posterior tibialis tendon is marked with yellow and Achilles tendon is marked with blue (Gray et al. *1918).*

Dyal and colleagues (1997: 85) state that in the early stages of PTT insufficiency, there is usually swelling and tenderness in the medial aspect of the foot. They add that, as the disease progresses, the longitudinal arch depresses, calcaneus goes into valgus, and forefoot abducts.

> “With posterior tibial tendon (PTT) insufficiency, the peroneal muscles are unopposed and eversion of the subtalar joint occurs. Abduction of the forefoot follows, with a gradual elongation of the soft tissue and the medial longitudinal arch collapses leading to the development of an acquired flatfoot deformity” (Dyal *et al.* 1997: 85)

Lee and colleagues (2005: 91) note that, the adult acquired flatfoot is usually caused by pathological changes within the posterior tibial tendon, and therefore the dysfunction is usually bilateral. However, the research made by Dyal and colleagues (1997: 87), revealed that the values of the feet with PTT insufficiency correlate strongly with the values of the asymptomatic feet. They used the asymptomatic feet of the patients as a control material and concluded that a preexisting flatfoot might be a factor causing PTT insufficiency.

McCormack and colleagues (2001: 17) state that PTT deformity might only be part of the problem and not the original cause. According to them, PTT would mostly have to do with the later stages of pes planus deformity. Park and colleagues (2013: 103) also note that in addition to the tibial tendon insufficiency, complex changes are involved in the foot architecture. They add that static stability of feet comes from the structure of soft tissue and bony anatomy.

Even though the deformity is complex and there are various reasons behind it, the formation can be simplified. As stated by Van Boerum and Sangeorzan (2003: 429), there are supporting structures like the bony arch, ligaments and muscles, which maintain the normal functions in the foot. Additionally, they add that there may be weaknesses in these structures, which might lead to a depressed longitudinal arch and therefore altered biomechanics. Van Boerum and Sangeorzan (2003: 429) also list the main factors as: increased bodyweight, PTT insufficiency, increased triceps surae tension, and looseness in the spring ligament or other supporting ligaments. Finally, they simplify the formation by stating that not enough support to the arch combined to excessive force that flattens the arch, results in a flat foot.

This study aims to figure out whether flatfoot deformity can be detected from bones alone. When a flatfoot diagnosis is made, doctors use radiographs, visual observations, and palpation to evaluate (Lee *et al.* 2005: 79,83). However, when studying archaeological specimens, we only have the access to bones and sometimes only fractures of them. Therefore, it can be challenging or even impossible to diagnose the reasons behind pes planus.

It is still widely researched and debated whether a change in an independent bone or in the overall posture of the foot was a cause or an outcome. For example, it is hard to tell if PTT insufficiency and the lack of stability caused the medial longitudinal arch to lower, and therefore affected into the formation of morphological changes in independent bones, or maybe a deformed bone caused a medial longitudinal arch to collapse, which inflamed the PTT. Therefore, this research only focuses on detecting the outcome; independent morphological changes, depressed medial longitudinal arch, and calcaneus in valgus.

3.3 Biomechanics

Biomechanics is a field that studies movement and structure of humans, animals, plants, and individual cells (Alexander 2005: 616). Alexander explains that, biomechanics are used in studies to learn more about functions, but also to solve practical problems. He details the use of engineering in biology and brings out dynamics, which can be used in the study of movements. Studying the biomechanics of feet and pes planus offer information about the changes in the movement and loading of people with flat feet. These studies may offer material to help prevent injuries of affected feet.

There are two joints that operate the movements of the ankle (Van Den Bogert *et al.* 1994: 1477). According to Van Den Bogert and colleagues, these joints are the subtalar joint, which consist of talus and calcaneus, and the talocrudal joint, which consist of talus, tibia, and fibula. They add that the ankle joint complex works with three rotations that are abduction and adduction, plantar- and dorsiflexion, and inversion and eversion.

On a normal foot, the gait cycle is separated into two phases (Van Boerum & Sangeorzan 2003: 420). As stated by Van Boerum and Sangeorzan, the weight-bearing part, called stance phase, starts at heel strike and lasts until toe-off. They add that this phase has three subdivisions; heel-strike, foot-flat, and heel-rise. The phase that starts from toe-off and ends at heel-strike is called a swing phase (Van Boerum & Sangeorzan

2003: 420). Foot is flexible throughout the early stance phase, but it becomes rigid for a toe-off and a forward propulsion (Jastifer & Gustafson 2014: 203).

During a heel-strike, calcaneus moves into a more everted position, moving cuboid, which causes the forefoot to abduct and the medial longitudinal arch to flatten (Van Boerum & Sangeorzan 2003: 420). Pedowitz and Kovatis (1995: 293) also note that the transverse tarsal joint[5] unlocks, which acts as a cushion for the impact. At the same time, eccentric[6] muscle work happens, also providing cushioning and control for heel-strike (Van Boerum & Sangeorzan 2003: 420).

Lindstedt and colleagues (2001: 257) state that a shock absorbing spring complex is created by an active muscle during eccentric contraction. They add that there are two ways how the mechanical energy absorbed from eccentric contraction work. First, the muscle can act as a shock absorber if the energy is dissipated as heat (Lindstedt *et al.* 2001: 256). Second, if the absorbed energy is stored temporarily and returned as recoil energy, muscle will act as a spring (Lindstedt *et al.* 2001: 256; Alexander 2005: 88).

Ledoux and Hillstrom (2002: 1) state that the loading of the foot should start from the heel and the subcalcaneal tissue, and progress to the forefoot, which means that the subhallucal and submetatarsal tissues distribute the loading together with the subcalcaneal tissue. Meanwhile, the tibia moves from internal rotation into external and calcaneus inverts, which locks the talonavicular and calcaneocuboid joints (Pedowitz & Kovatis 1995: 293). As stated by Pedowitz and Kovatis, this solidification of the arch provides a rigid a toe off.

Finally at a heel off, the weight is spread through the toes and metatarsal heads until just before toe off it transfers almost entirely to hallux (Ledoux & Hillstrom 2002: 1). The study of Ledoux and Hillstrom (2002: 2) points out that the part where ground reaction force affects a foot with pes planus, has been suggested to be more medial than on a neutral feet. They conclude that the subhallucal loading appears increased compared to neutral feet.

On a foot affected by pes planus, the gait differs from normal. As stated by Van Boerum and Sangeorzan (2003: 423), flattening of the longitudinal arch also means that the arch

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[5] Talonavicular and calcaneocuboid joints (Stephen *et al.* 2010: 91)

[6] The force produced by the muscle is exceeded by a force applied to the muscle, which causes the muscle to lengthen (Lindstedt *et al.* 2001: 256).

becomes longer. They add that the head of the plantar flexed talus is no longer supported by the calcaneal anterior process. Due to lengthened medial longitudinal arch compared to the fixed length lateral column, forefoot becomes abducted towards the lateral column (Van Boerum & Sangeorzan 2003: 423). However, Van Boerum and Sangeorzan (2003: 423) note that the PTT (posterior tibial tendon) is a strong structure that should counteract these changes. Still, a pre-existing flatfoot or too much stress on the PTT might lead to a degeneration of the tendon.

According to Van Boerum and Sangeorzan (2003: 422), an existing flatfoot deformity alters the stance phase of gait. They detail that for a normal propulsion to happen during heel-rise, the arch needs to be inflexible. However, with a flattened arch and a PTT insufficiency, inversion during midstance is decreased and the effectiveness of a normal gait lost (Van Boerum & Sangeorzan 2003: 422). Therefore, when the support of the arch is weakened, propulsion during gait is decreased and the flattened arch is unable to work as a cushion for the impact of activities (Van Boerum & Sangeorzan 2003: 421, 422).

4. METHODS

Both clinical and physical examinations are used when flatfoot is diagnosed on living individuals according to Lee and colleagues (2005, 79, 83). They state that on and off weight bearing evaluations on radiographs show the condition of the foot, which can be further evaluated through physical examination. The pes planus characteristics that can be noted by physical examination, are depressed medial longitudinal arch, valgus heel, and abducted forefoot (Lee *et al.* 2005: 79).

However, when diagnosing flatfoot deformity from bones alone, osteoarchaeologists are not able to use weight bearing radiographs or palpate the foot. Clinical diagnoses are easier to make than paleopathological ones because of more information, but wrong diagnoses still exist (T. D. White & Folkens 2005: 310–11). White and Folkens note that, there are difficulties in finding well documented reference material, and in finding manifestations on bones, that would link to specific diseases.

This research comprises of three bones of the ankle and foot (figure 2). At first, the tali, calcanei, and naviculars were measured. These are the ankle and foot bones that have a big effect on pedal posture and are often affected by the changes of flatfoot deformity. Tali, calcanei and naviculars were also best present in the material and are frequently used when making clinical diagnoses of flatfoot deformities.

After the measurements had been taken, the bones were pictured to calculate angles between them. Tibiae were also used to align the bones into their anatomical positions in posterior pictures of the ankles. These pictures were taken in a way that the positioning of the bones resembles normal bone anatomy seen in radiographs. After the measurements and pictures were taken, they were analyzed. Angle measurements were calculated from the pictures using QCAD computer program. For statistical analyses the program IBM SPSS 23 was used.

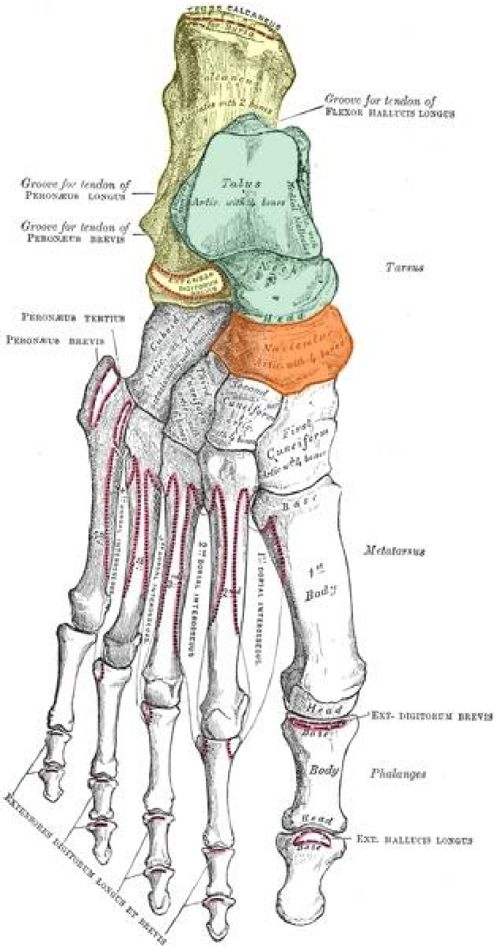


Figure 2. Dorsal view of right foot shows navicular (orange), talus (green), and calcaneus (yellow). (Gray et al. *1918)*

All the angles that were measured in this research can also be measured from a radiograph taken from a living person. However, the stabilizing effect of soft tissue for the posture needs to be noted. Therefore, the exact percentages indicating pes planus that are used in medical cases could not be used in this study. Neither were any bones able to be used as a reference material in this study. No evidence on ankle bones being studied this way before was found. Therefore, there were no valid results for pes planus and controls that could have been compared to the results for this method.

The reference measurements that I used were from articles where radiographs taken from living people were studied. Most of these studies were medical studies to determine the morphology of feet affected with pes planus. While the pictures in this study were taken to resemble positions in radiographs, the results from radiographic measurements are used, but with high caution. The results that the angle measurements offered were examined for any extremes and to see if any specific bone or leg would stand out and give an indication of pes planus.

4.1 Measurements

TALUS

Talus is located in a central place for foot movement. According to Van Den Bogert and colleagues (1994: 1477), two separate joints comprise the ankle joint complex in humans, and talus in involved in both of them. Talus is positioned in a way that changes in the posture of the ankle and the foot usually influence talus. It is second largest of the tarsals and it forms joints with calcaneus, navicular, tibia, and fibula.

Multiple studies have been made to clarify whether the length of talus would be longer compared to the width on a foot affected by pes planus. Ponnapula (2012: 320) agrees to this claim with Anderson and colleagues (1997: 706), while Peeters and colleagues (2013: 284) are against it. The measurements of the tali in this study, were taken according to the guidelines used by Anderson and colleagues (1997: 706).

The characteristics observed from tali in this study, were the morphology of the bone, some aspects of the talonavicular joint, and the relationship between talus and calcaneus. Six measurements taken from all tali, and measurements from eversion facets when present, offered an encompassing knowledge of the bones. The bones were otherwise in a good condition, but unfortunately eversion facets from two tali could not be measured due to poor preservation.

Tali were measured from two angles (figure 3). Firstly, the length was measured from the tip of the lateral tubercle to the head of talus, and from the sulcus for flexor hallucis longus to the head of talus. Width of the bone was measured from the tip of lateral process and from the lateral border of the articular surface with distal tibia to the medial border of talus. By taking two measurements of the width, it is possible to get a comparable measure of the width of the lateral process. Additionally, height was also measured from the tali. The overall height was measured from the tip of the lateral process to the top of the tibial articular facet. The height of the lateral process was also measured.

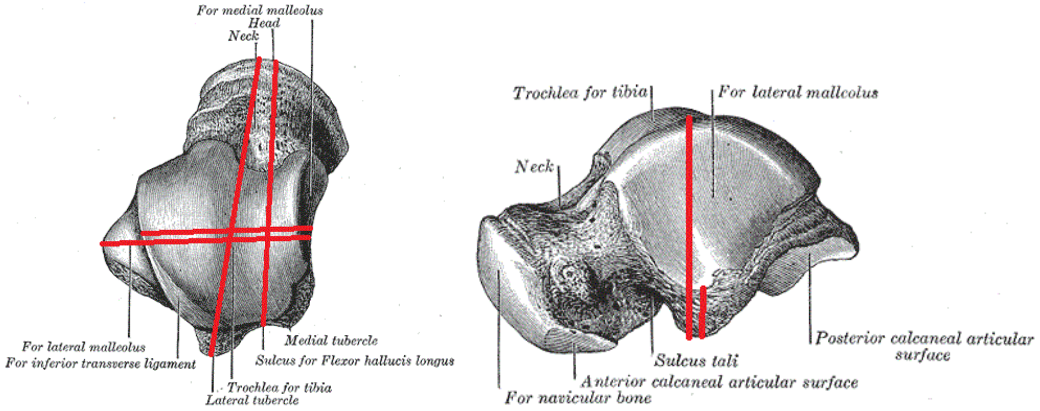


Figure 3. Measurements taken from tali.(Gray et al. *1918)*

There are also additional facets, called eversion facets that were measured from tali if they were present. The facets were also compared with the angle measurements to observe if the existence of the facets would correlate with the angles indicating pes planus. Darton (2007: 287) states that the facets form when constant contact between the talus posterior articular surface and the edge of the sinus tarsi takes place (figure 4) These facets are called accessory anterior facets (*facies accessoria corporis tali*) or eversion facets and they are linked to pes planus (Darton 2007: 294, 296; Martus *et al.* 2008: 2452). According to the study of Martus and colleagues (2008: 2456), eversion facets are more common on male donors. This could also be linked with the bigger number of males suffering of pes planus compared to females (Tenenbaum *et al.* 2013: 814).

The study by Darton (2007) also raised some questions. Darton (2007: 287) only chose bones from seven individuals into the study and the bones were all abnormal. The bones were very affected morphologically and showed severe changes. These changes included osteoarthroses and even bones with neoarthrosis. The measuring of these facets in this research, will hopefully give indications on whether eversion facets can also be found on asymptomatic feet, or are they always connected to pes planus.

Figure 4. Eversion facet on a talus.

CALCANEUS

The measurements taken from calcanei (figure 5) were total length, and total width from the widest part and from the narrowest part. The widest measurement was taken perpendicularly from the tip of the sustentaculum tali and the other width measurement from the narrowest part of the bone. These measurements give a general view of the size of the bone. Additionally, the relation between the length and the total width can be measured. Hypothesis is, that subtalar subluxation and the posterior subluxation of calcaneus might cause changes in the width of the calcanei, and even more specifically in the *sustentaculum tali*.

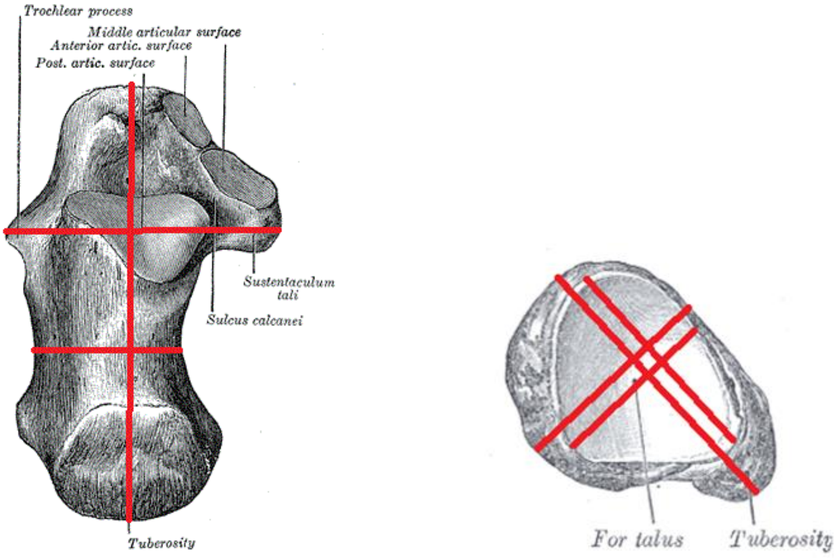


Figure 5. Measurements taken from calcanei and naviculars. (Gray et al. *1918)*

NAVICULAR

Measurements taken from naviculars (figure 3) consisted of overall length and width of the bone, and the length and width of the talus articular facet. These measurements were taken to see if they would indicate how well the talus articular facet of navicular covers the head of talus. This was trusted to be possible by calculating the percentual size of the articular facet compared to the overall proximal navicular. The percentage could offer insight about the talonavicular joint coverage on naviculars.

Length 1 was multiplicated with width 1 to get a referential area of the talar articular facet. Length 2 was then multiplicated with width 2 for an overall area of proximal navicular. It should be noted that these calculations are suggestive and are only used to compare the size of articular facet to proximal navicular.

4.2 Reconstructions of radiographic layouts

Park and Schon (2013: 109) indicate that radiographic evaluation should be used as a way to determine the existence of a flatfoot deformity. Lee (2005: 83) adds that, radiographs might also be used as a means of determining the degree of the deformation after a positive diagnosis has already been made.

Lee and colleagues (2005: 83) use multiple measurements from radiographs, but only a few of those measurements are possible to detect straight from the bones. The radiographs that are usually taken include weight bearing standing dorsoplantar, lateral, and oblique views (Lee *et al.* 2005: 83). Additionally, if ankle valgus is suspected, posterior ankle radiographs might be taken (Lee *et al.* 2005: 83). Park and Schon (2013: 109) note that angles formed by different bones can be measured and evaluated from the radiographs.

Pictures for this research try to mimic the positions in the radiographs. Angle measurements are also calculated in a way that most closely resembles the radiograph conditions. It is still easier to evaluate the presence of a flatfoot deformity from a weight bearing radiograph with the whole foot present than from individual bones. However, when determining midlines of tali and calcanei from radiographs, intra observer error must be noted. It might sometimes be difficult to detect the borders of ankle bones in dorsoplantar radiographs.

There are several criteria found from the radiographs that would indicate flatfoot deformity according to Lee and colleagues (2005: 83). These include the increase of the talocalcaneal angle and the talo-first metatarsal angle, which can both be seen in dorsoplantar (DP) and lateral radiographs. However, talo-first metatarsal angle measurements cannot be reliably used in this research. To do so, the whole foot would have to be reconstructed. Reconstructing the whole foot would have been too complicated and time consuming. Therefore, this research is only concentrated on certain bones and their connections. As stated by Lee and colleagues (2005: 83), other means of evaluation from radiographs include decreased calcaneal pitch, degree of talar head coverage, the continuity of *cyma* line, and the appearance of tarsal coalition.

The cyma line (figures 6 and 7) is a term of a line that can be noticed as a union between the curves of talonavicular joint and calcaneocuboid joint (Van Gestel *et al.* 2015: 182). According to Van Gestel and colleagues, It should show as a smooth line between the joints in both lateral and dorsoplantar views. They note that a disrupted cyma line could suggest a rotated talus, and therefore calcaneus seems shorter. This is usually seen as an indicator of pes planus.

Figures 6 and 7. Lateral cyma-line on a foot with normal arch (left) and on a foot suffering from pes planus (right). http://uwmsk.org/footalignment/doku.php?id=pes_planus, used with CC Attribution-Noncommercial 4.0 International –license.

Park and Schon (2013: 109) add that, flatfoot deformity might often be more significant than is seen from the radiographs. Therefore, additional pictures and videos of the feet and other observations are regularly needed to determine the state of the deformity (Park & Schon 2013: 109). If the degree of the condition does not even fully correlate with the weight bearing radiographs, the results from the bones alone must be extra carefully evaluated.

The angle measurements that are used in this research include pictures from several views (table 1). Firstly, the evaluation of talocalcaneal angle (A, A2, and B) from two sides uses dorsoplantar (DP) and medial pictures. Talocalcaneal angle is a common angle to be measured from the radiographs of patients suspected to have pes planus (Lee *et al.* 2005: 83). A bigger talocalcaneal angle measured straight from bones might therefore indicate the possibility of pes planus. Secondly, the posterior evaluation of the angle between calcaneus and tibia (C) is made from posterior pictures. Lastly, the angle of talar head compared to talus body (D and E) is measured from distal talus pictures and dorsoplantar pictures. However, these angle measurements only represent a two-dimensional view of a deformity which is more complex than that. Therefore, they need to be compared with other results to make any conclusions.

Table 1. The directions and definitions of angles measured.

Angle	Direction	Definition
A	dorsoplantar	talocalcaneal angle
A2	dorsoplantar	talocalcaneal angle, talus in natural extreme position
B	medial	talocalcaneal angle
C	posterior	tibiocalcaneal angle
D	distal	talar head to body
E	dorsoplantar	talar head to body

4.2.1 Dorsoplantar (A, A2)

DP pictures (figures 8 and 9) were all taken using the same guidelines. Tali and calcanei were positioned in their anatomical positions in a way that the tibial articular facet of talus was in level. There was a slight 10 mm elevation used under the distal head of calcaneus for a more natural position. Pictures were taken straight from above. Talar axis was measured along the medial end of the talar body and calcaneal axis along the lateral surface of calcaneus. The angle between these two axes was measured from the pictures in a computer program. However, it needs to be remembered, that without the tendons and other tissue surrounding the bones, positioning is always open for intra and inter observer errors.

In the DP pictures where angles A were measured from (figure 8) tali were positioned on top of calcanei to a position where they would naturally sit. The positions of the bones were reconstructed on the basis of how the bones would fit the most natural.

These pictures are attempting to mimic the placement where the bones are at in the non-weight-bearing radiographs.

Additionally, also the bones were pictured on another way at dorsoplantar view (figure 9). These pictures were taken in order to resemble the everted position where talus would be in a weight-bearing radiograph. Subluxation happens while calcaneus rotates externally and talus rotates internally to cause an everted hindfoot position (Martus *et al.* 2008: 2458). This subluxation would hopefully show in the A2 angle measurements calculated from these pictures. A study by Ananthakrisnan and colleagues (1999: 1153) detail that a symptomatic flatfoot and a weak tibialis tendon may cause subluxation of the talocalcaneal joint during weight-bearing. The pictures were taken the same way as the first ones, except that tali were positioned in their natural extreme medial position. The extreme natural positions were laid out on the basis of how far medially the tali would smoothly evert to.

Figures 8 and 9. On the left is a DP picture with angle A in 21°. On the right is a DP picture with angle A2 in 34°.

The weight-bearing radiograph would show medial shift of a talar head and a loss of navicular coverage as shown in figure 10. In the A2 pictures of this study, the bones are supposed to be in the position as they would be while bearing weight in walking or running, thus during the exercises where pes planus would manifest. A2 angles were also measured from the pictures using a computer program.

Figure 10. Non-weight-bearing DP radiograph (left) compared to weight-bearing (right) from a person suffering from posterior tibial tendon insufficiency. Note the position of talus compared to navicular. Reprinted by permission of https://pttdfootsurgery.wordpress.com/.

4.2.2 Medial (B)

For medial pictures, the bones were easier to position. They were put on sand horizontally and the pictures were then taken straight from above. On medial view, talocalcaneal angle can be measured from the side. As stated by Lee and colleagues (2005: 83), in pes planus talocalcaneal angle is increased in lateral view. However, medial view was easier to photograph in this case. Calcaneal axis was measured along the plantar surface and talar axis along the dorsal surface. Angle B was then calculated between these two axes (figure 11).

Figure 11. Medial picture with angle B.

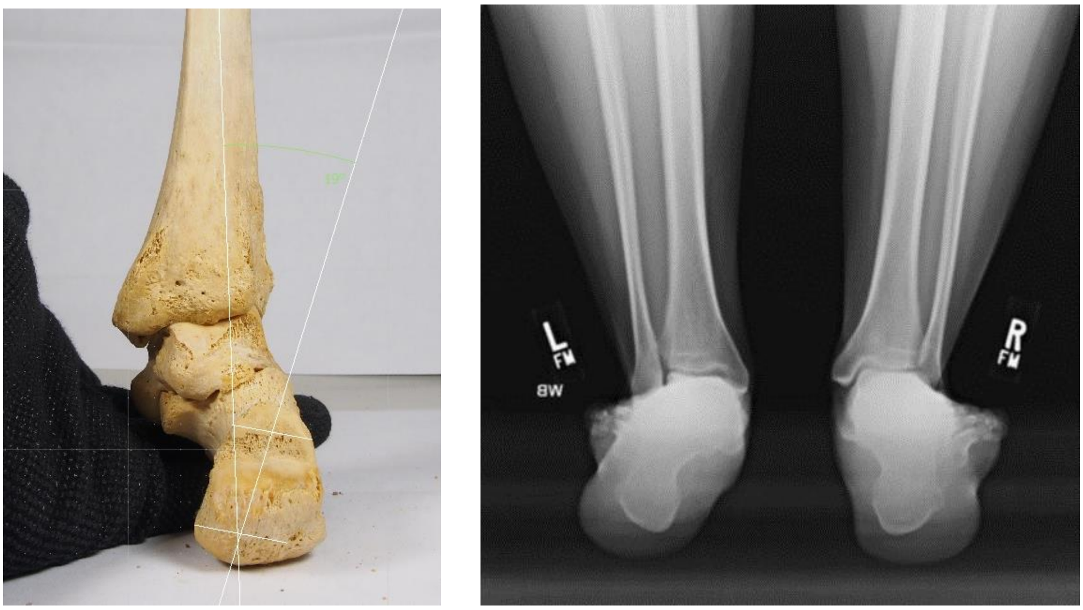
These pictures also show if talus has rotated and shifted forward, and therefore would interrupt the medial cyma-line (figures 12 and 13). According to Van Gestel and colleagues (2015: 182), the midtarsal joint on a foot without pes planus should form a smooth curvy line on both lateral and dorsoplantar views. Medial pictures were trusted to give the same indication about interrupted cyma lines than lateral ones.

Figures 12 and 13. Medial view of tali and calcanei. Note the tilting and forward shifting of talus on the right-side picture. As the tilting happens, it also has an effect on the cyma-line, which is marked with red.

4.2.3 Posterior Ankle (C)

Positioning bones for posterior pictures required more work than for the other pictures. Here tibiae were also used with calcanei and tali to picture the relations of the bones. Tibiae were held vertically, and fingers were used as elevation under calcanei. These pictures (figure 14) show the relations of calcanei and tibiae posteriorly, and the eversion angles of calcanei.

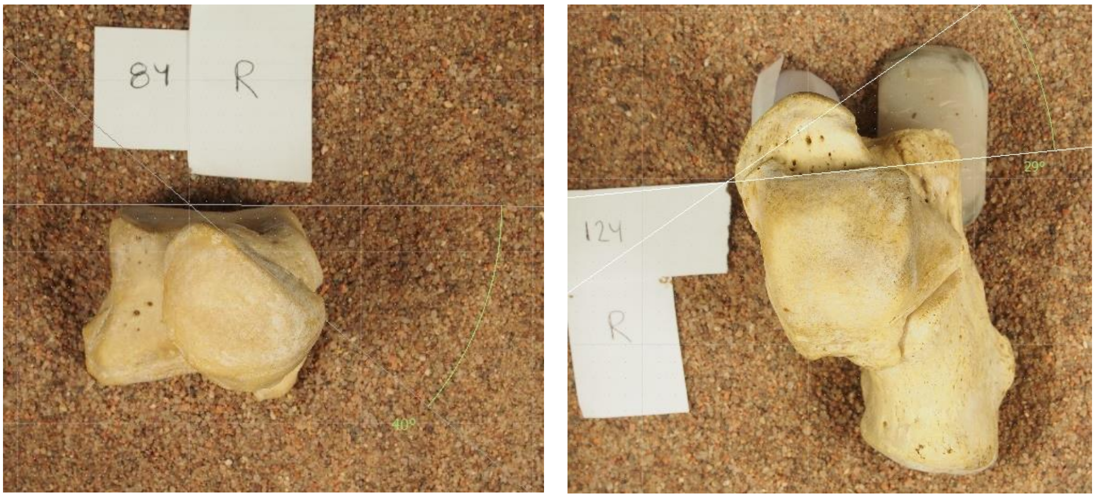
The long axis of tibia was defined using perpendicular lines on two parts of the shaft and drawing the axis through them. Same was done to the posterior part of calcaneus. Finally, the angle between these two axes was measured. Lee and colleagues (2005: 83) note that, if angle valgus is suspected, posterior radiographs help in determining pes planus (figure 15).



Figures 14 and 15. A posterior picture with angle C on the left. A hindfoot radiograph on the right (Vulcano et al. *2013). Radiograph shows severe calcaneal valgus on the left foot and a milder condition on the right foot.*

4.2.4 Distal Talus (D)

The morphology of talus is affected due to flatfoot deformity (Peeters *et al.* 2013: 284). Peeters and colleagues add that, the articular facet on talar head tends to face more proximally in affected bones. Distal picture of talus makes it possible to evaluate the angle between talus head and talus body and see if there is any correlation with other results. The axis of talar head was measured along the dorsomedial side of the head and the axis of talar body along the dorsal surface (figure 16). After these axis were measured, the angle between them was calculated.



Figures 16 and 17. On the left, a picture of distal talar head with angle D in 40°. On the right there is the angle E showing the angular position of talar head to body in transverse plane.

4.2.5 Talus DP (E)

The angle E between talus head and talus body was also measured from dorsoplantar pictures (figure 17). With this angle measurement, it may be possible to study the hypothesis, that the angle of the head of talus might get morphological changes due to subluxation seen in pes planus.

The dorsoplantar pictures for the angle E measurements were the same where angles A and A2 were measured from. Therefore, the articular facet of tibia in tali were in level. To measure the angular position of talar head, the perpendicular axes of talar body and head had to be set. The axis of talar body was measured somewhat along the distal end of talar body, however the axis was drawn approximate if the tibial articular surface was vague on the medial distal part. The transverse axis on talar head was drawn as an estimate of a perpendicular axis of talar head.

5. MATERIAL

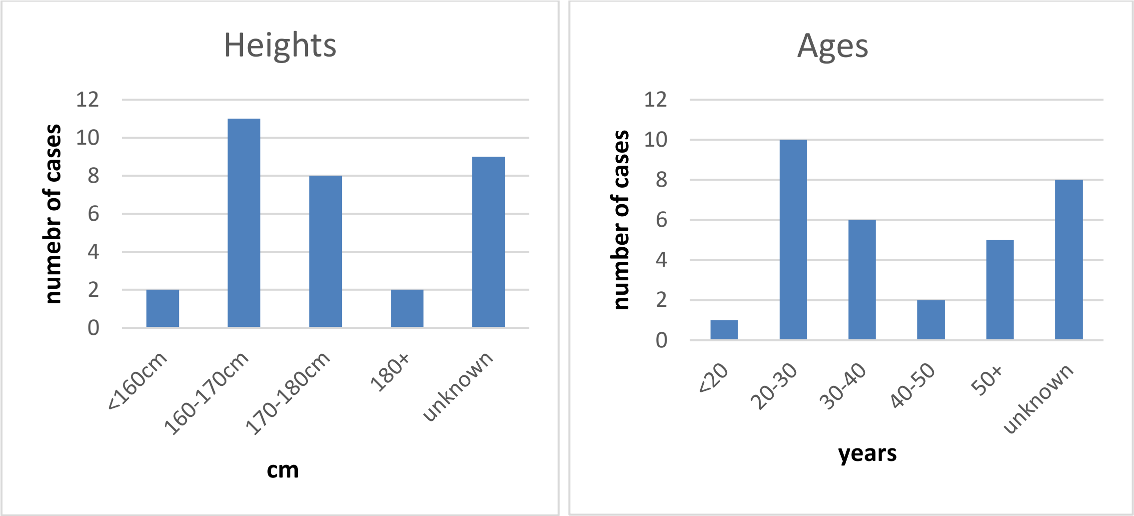
The material that was used in this research is part of the University of Helsinki human remains collection located in the Natural History Museum in Helsinki. This collection is the most extensive, informative, and best-preserved human remains collection in Finland. It is easily accessible for researchers and is currently under-utilized. It is valuable to have bone collections to study, because taking radiographs from living individuals for studying purposes is not as ethical.

The series A of the collection contains 201 individuals whose identities, sexes, and often also professions, ages at death, and heights are known (Söderholm 2002). According to Söderholm, most of the bones were once used as teaching material. He details that almost all of the skeletons were collected during two periods in the early 20th century, 1914-1916 and 1928-1937. Almost half of the individuals were prisoners who died in one of the prisons in Finland, and the rest of these skeletons came to the collection from hospitals and retirement homes from all around the country (Söderholm 2002).

In the series A –collection, there are 147 males, 42 females, and 12 individuals of unknown sexes (Söderholm 2002). Their mean age is 44.8 years (42.8 male and 52.6 female) and they have a mean height of 166.7 cm (169.7 cm male and 156.6 cm female) (Söderholm 2002). These statistics are also shown in figures 18 and 19.

From 201 individuals in the series A, 31 were preserved well enough for this research and contained both calcanei, tali, naviculars and tibiae. In addition, one individual was included who had all the other bones for this research except for other tibia. 31 of the skeletons were male and one was female. All in all, the sample size consisted of 32 individuals, which means that 64 feet were studied.

The ages at death of the individuals is known from 24 individuals out of 32. Their ages vary between 17 and 77 while the mean age is 36.3. Persons between 20-30 years of age form the biggest age group. The heights of 28 individuals out of 32 are known. Their heights have variation from 156 cm to 182 cm, the mean height being 168.8 cm. The heights will give an extra variable for the research on flatfoot deformity. Most of the individuals come from similar backgrounds, since 11 of them are marked as inmates. Other types of backgrounds that are listed in the additional information of them, include workers, idler, and an electricity technician. Even with all this information about the individuals, there is still no knowledge on how their pedal health was while they were still alive.



Figures 18 and 19. The heights and the ages of the individuals in the research material.

The bones have never been buried and are in an excellent condition. Almost all the bones still have all articular facets intact, which made taking measurements easy. The bones that were used in this research, were measured using the same guidelines. After the measurements were made, they were used for pictures, where more than one bone were pictured in their anatomical position.

6. RESULTS

6.1 Talus

The lengths of the tali were measured from the sulcus for the flexor hallucis groove all the way to the talar head (Shapiro-Wilk[7], p=0.060), and they were compared with the widths measured perpendicularly from the most lateral tip of the lateral process (Shapiro-Wilk, p=0.088). The comparison (figure 20) shows that the talus on the right foot of the individual number 33 seems to be longer compared to the width than the other tali. The rest of the measured tali do not stand out, except numbers 37 & 38, which belong to a female (146) and are noticeably smaller than the others.

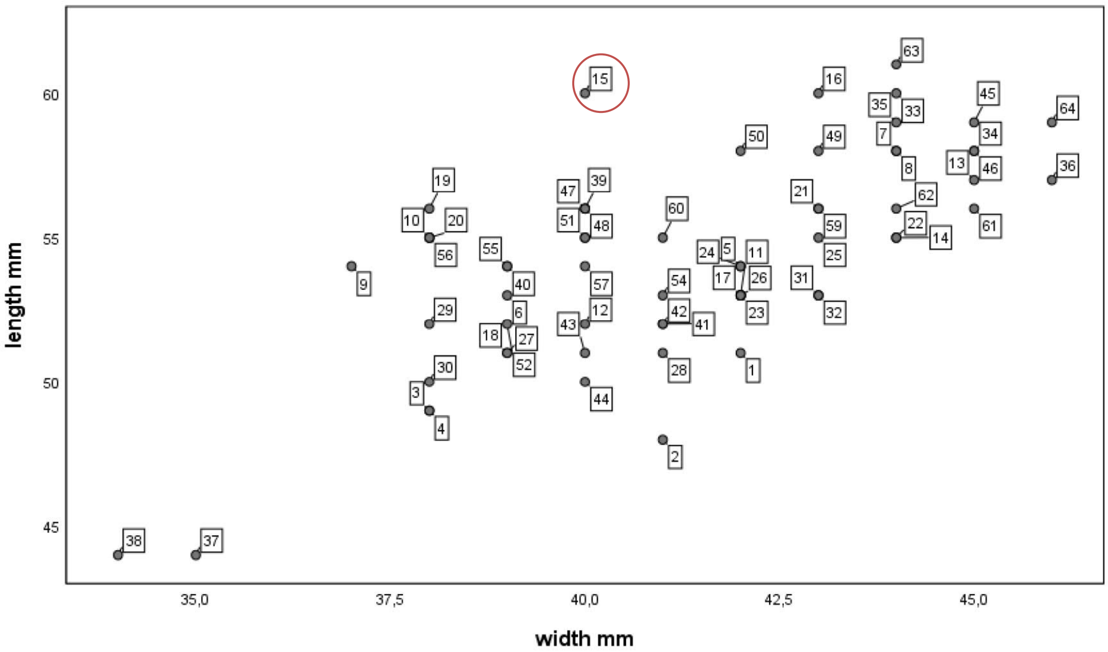


Figure 20. A scatterplot graph of talus length and width compared. Talus number 15 (33 right) seems to be longer compared to width than the other tali. 37 and 38 belong to a female and therefore stand out as smaller than the other.

The angle of talar head to body was also measured on two sides: the dorsoplantar view as angle E (Shapiro-Wilk, p=0.174) and the distal view as angle D (Shapiro-Wilk, p=0.892). These angle measurements gave results of the relationship and the angular position of talar head compared to body on the transverse plane and the frontal plane, respectively. There was a preceding thought that these measurements on the angular positions of talar heads might correlate to some extent. The results are seen on figure 21. There is no correlation according to the results of Pearson correlation (table 2), but Spearman's rank correlation coefficient however, showed a negative statistical relationship of p=0.032 (table 2). The Spearman's rs indicates a monotonic relationship

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[7] Test of normal distribution. The measurements follow normal distribution if p>0.05.

that does not have to be linear (Meyers *et al.* 2013: 165). The results point to the direction that if a talar head is more angular to talar body at the transversal plane, it is less angular at the frontal plane.

Table 2. The correlation between the angles E and D.

	N	Pearson r		Spearman rs	
E/D	64	-0.220	p=0.080	-0.269	p=0.032**

** Correlation is significant at the 0.05 level

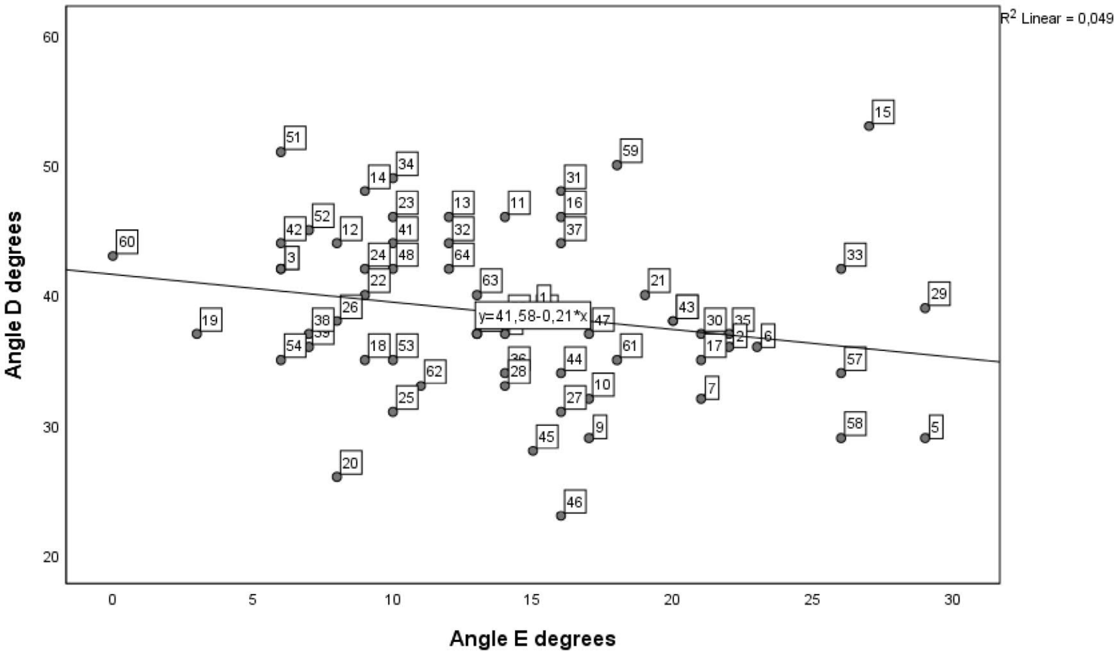

Figure 21. A scatterplot graph of the comparison between the angles D and E.

The angle D measurements from distal talar heads were compared to the widths of the talus lateral processes out of curiosity (figure 22). Both variables were normally distributed according to Shapiro-Wilk test. The result for Pearson correlation test shows a statistical significance of p=0.004 with a weak correlation of 0.355 (table 3) (appendix 5). This would indicate that the wider the lateral process is, the bigger the talar head to body angle is. The widths of the lateral processes were also compared with other measurements taken from tali, but no additional correlations were observed.

Table 3. The correlation between talus head to body angle (D) and the width of talus lateral process.

	N	Pearson correlation	p
D/talus lat. w.	64	0.355	0.004**

** Correlation is significant at the 0.05 level

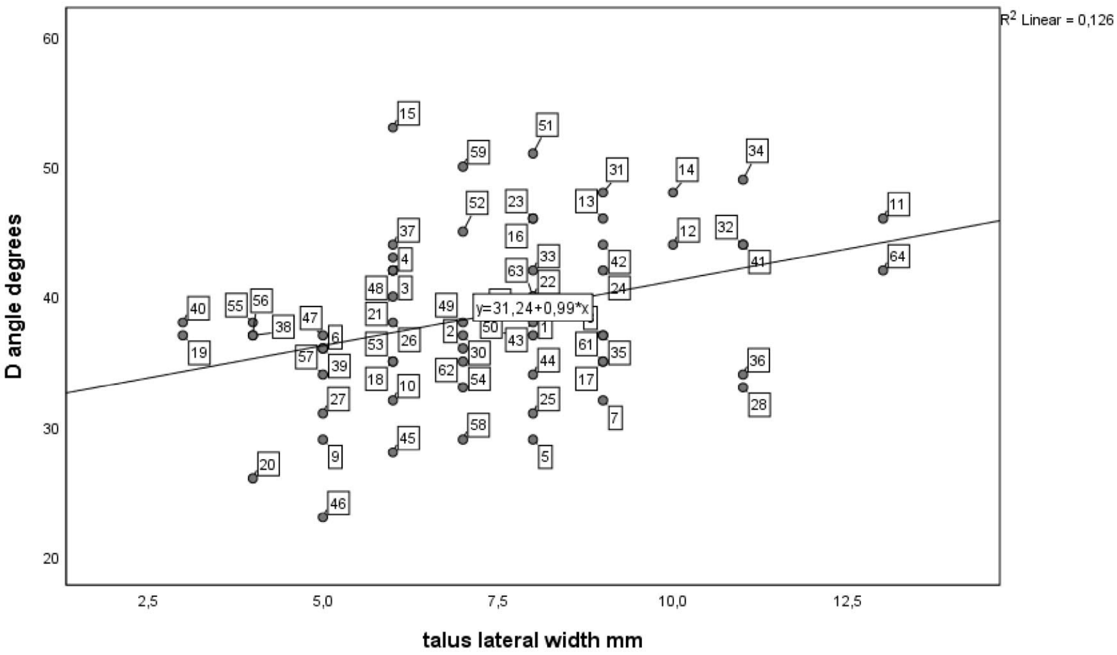

Figure 22. A scatterplot graph of the correlation between the angle D measurements and the width measurements of the talus lateral processes.

Eversion facets were found on 35 tali out 64; 17 on the right tali and 18 on the left tali (appendix 3). Nine individuals had eversion facets only on the other talus. Only nine individuals out of 32 did not have them at all. The size of the facets varies between 15mm x 7mm to 6mm x 3mm. All angle measurements were normally distributed according to Shapiro-Wilk test (see table 4), except the angle E. All of the angle variances were equal according to the Levene's test (see table 4). However, ANOVA F-test (for angles A-D) and the Brown-Forsythe-test (angle E) revealed that the difference between having an eversion facet and not having one, was not significant in any of the cases (see results in table 4).

Table 4. A table showing the relationship that the existence of eversion facets have on the angle measurements.

Angle	p (Shapiro-Wilk)	p (Levene)	p (ANOVA-F)	p (Brown-Forsythe)
A	0,784	0,588	0,143	
B	0,695	0,801	0,209	
C	0,713	0,641	0,858	
D	0,868	0,582	0,587	
E	0,036**	0,572		0,924

** Significant at 0.05 level

Additionally, left talus on the skeleton number 1719 had formed an osteophyte into the lateral head and neck area (figure 23). It looks like the navicular would have shifted more proximally and caused extra growth into talus in order to accommodate the subluxated bone. Darton (2007: 296) has presented a similar, but a more severe case in his study. He details that the growth has formed due to subluxated navicular bone causing neoarthrotic molding.

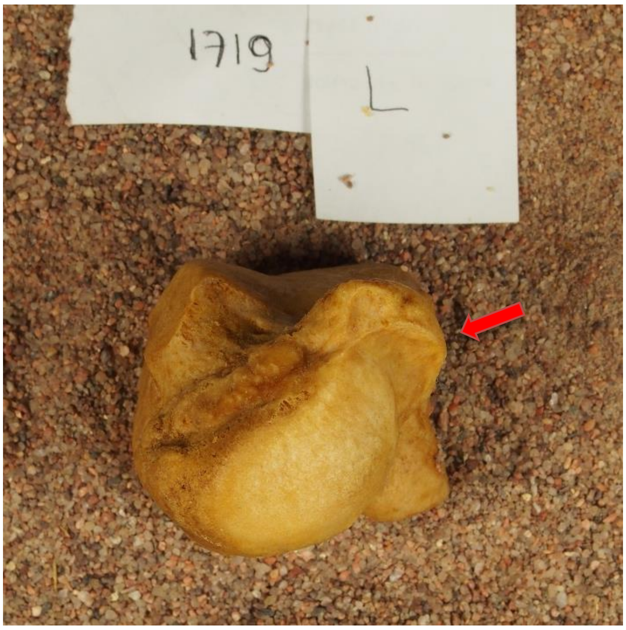

Figure 23. An osteophyte on talar head.

6.2 Calcaneus

Even though there is a lot of variation in the widths of the bones, the correlation between the length and the width of the calcanei seems to be weaker than estimated. On tali, the Pearson correlation between the length (Shapiro-Wilk, p=0.060) and the width (Shapiro-Wilk, p=0.088) is moderate (r=0.677, p<0.01), as would be expected. The bones that grow longer usually also grow wider, if they are not deformed or affected by an outside factor. The graph (figure 24) indicates that the widths (Shapiro-Wilk, p=0.012) and the lengths (Shapiro-Wilk, p=0.081) of the calcanei do correlate, but not strongly. Unfortunately due to the small sample size or for other unknown reason, the skewed distribution of the widths could not be corrected. For this, Spearman correlation coefficient was tested. The Spearman correlation is not as sensitive to outliers as Pierson is, and it shows a statistical significance of p=0.022 and almost a weak correlation of 0.287 (table 5) (appendix 5) (Meyers *et al.* 2013: 166). However, the results of the Spearman rs do not differ much from the Pearson r results (p=0.027). Additionally, the graph (figure 24) shows four calcanei that separate as wider from the others (15, 22, 7 & 8). This might also be due to genetic reasons.

Table 5. The correlation between the length and width of the calcanei.

	N	Pearson r		Spearman rs	
length/width	64	0.277	p=0.027**	0.287	p=0.022**

** Correlation is significant at the 0.05 level

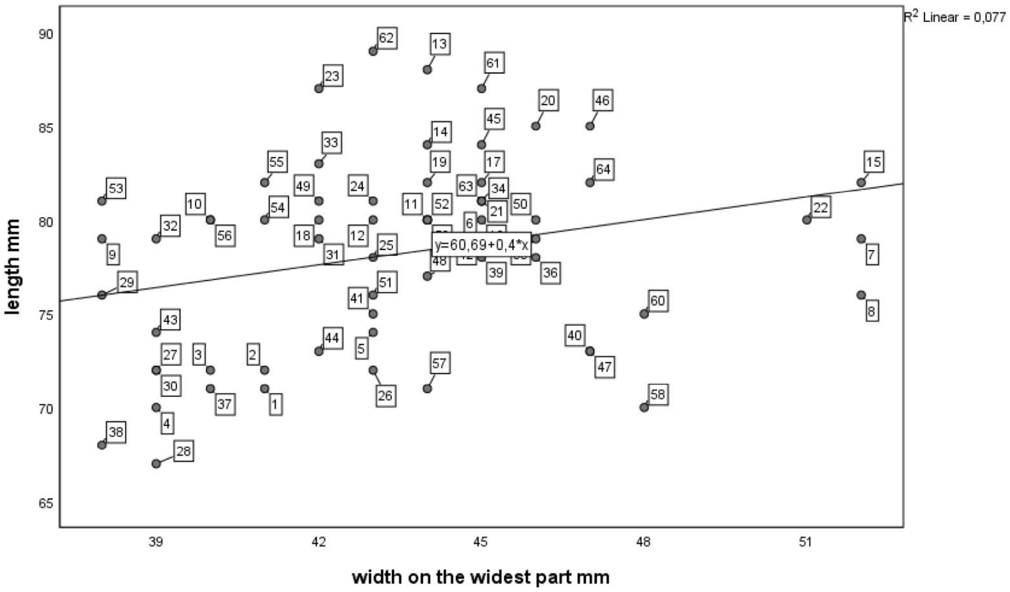

Figure 24. A scatterplot graph of the length of the calcanei compared to the width on the widest part.

The width on the widest part of the calcanei did also correlate with the angle A measurements (figure 25). The Spearman test shows a statistical significance of p=0.001 with a weak correlation of 0.418 (table 6) (appendix 5). This would indicate that the bigger the dorsoplantar talocalcaneal angle (A) is, the wider the widest part of the calcaneus is.

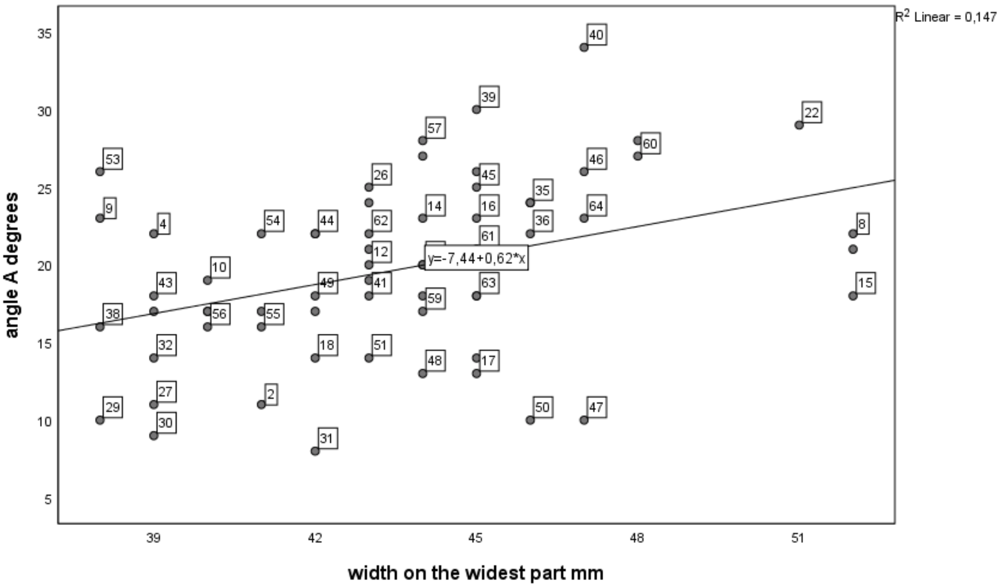

Figure 25. A scatterplot graph of the correlation between the angle A measurements and the widths of the calcanei.

Table 6. The angle A degrees compared to the widths of the calcanei.

	N	Pearson r		Spearman rs	
A/width	64	0.383	p=0.002**	0.418	p=0.001**

** Correlation is significant at the 0.05 level

Angle C was then measured from the posterior pictures. It represents the position where ankle bones would be in a non-weight bearing radiograph. The angle between the tibia and the calcaneus was measured. It was then compared with the width of the calcaneus to show if they would have a correlation. Despite the fact that the widths of the calcanei correlated with the angle A measurements and we know that the tibiocalcaneal angle (C) measurements are used to diagnose pes planus on radiographs (Lee *et al.* 2005: 83), there seems to be no correlation (p=0.191, Pearson -0.167) between the width of the calcanei and the angle C measurements (figure 26).

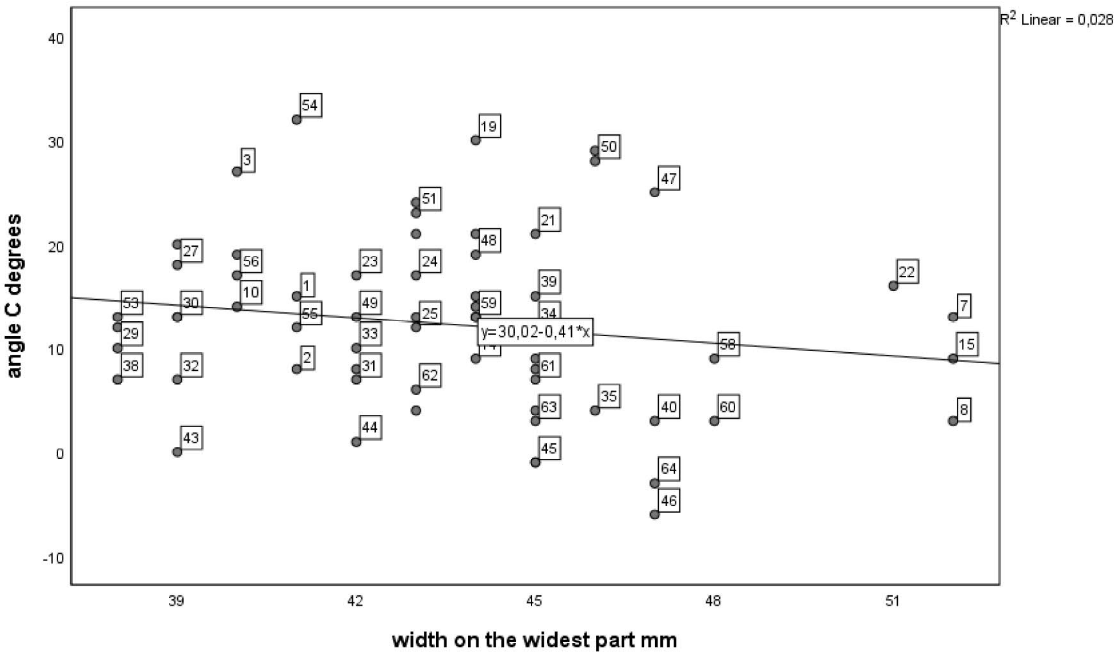

Figure 26. The width of the calcanei compared to the angle C (posterior tibiocalcaneal angle) measurements.

The individuals whose calcanei stand out as being wider than the others are 26r& l, 33r, and 84l. However, the measurements of their pedal bones show no any other indications for pes planus according to the results, except the right foot of an individual number 33. The talus number 33r also stood out as being longer compared to the width than the other tali (see page 32).

6.3 Navicular

The hypothesis is that the smaller the area of the talar articular facet is compared to the size of proximal navicular, the higher likelihood is there that the individual might suffer from flatfoot deformity. However, none of the measurements from this study correlated with the articular facet percent. The size of the talar articular facet on naviculars do not correlate with any of the other measurements either. Neither does the size of naviculars. However, the size of the naviculars correlate strongly (Pearson 0.850, p<0.001) with the size of the articular facets. Therefore, it can be assumed that the size differences of the articular facets are not a result of loss of talonavicular joint coverage. Bigger naviculars simply mean bigger articular facets and vice versa. This does not take into consideration the depth of the facets however.

6.4 Angles

Table 7. The descriptive statistics of all angles in this study.

Angle	N	Shapiro-Wilk	Minimum	Maximum	Mean	Std. Deviation
A	64	0.784	8	34	19.66	5.593
A2	64	0.392	20	41	31.02	5.187
B	64	0.695	31	63	48.08	6.748
C	63	0.713	-6	32	12.33	8.471
D	64	0.868	23	53	38.56	6.304
E	63	0.036**	3	29	14.44	6.342
Valid N	62					

** Significant at 0.05 level

As seen from the figure 27 the tali that have had the biggest increase in the angle measurements would have roughly been 47, 31, and 29. According to the percentual increase from angle A to angle A2 presented in a boxplot (figure 28), shows that the tali which stand out are tali number 31, 47, 29 and 30. However, if the angle A is small, A2 does not need to have a big increase to seem significant according to the percentual increase. From the ones that seem significant according to the percentages, 56 is the only one with a bigger angle A to begin with.

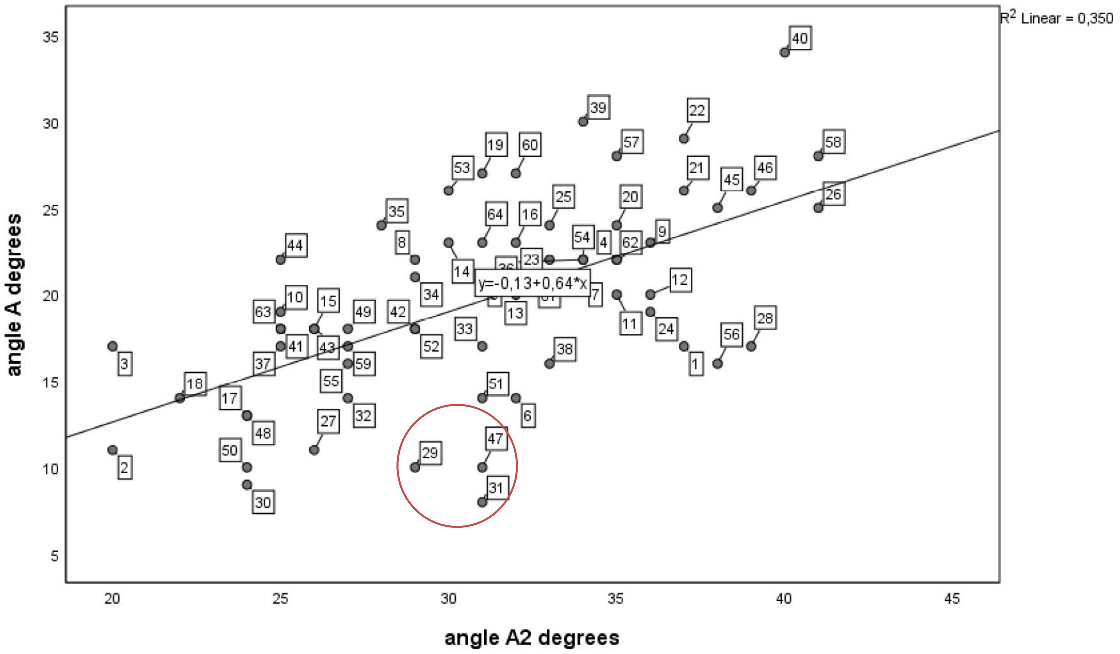

Figure 27. A scatterplot graph of the angle A and the angle A2 degrees compared

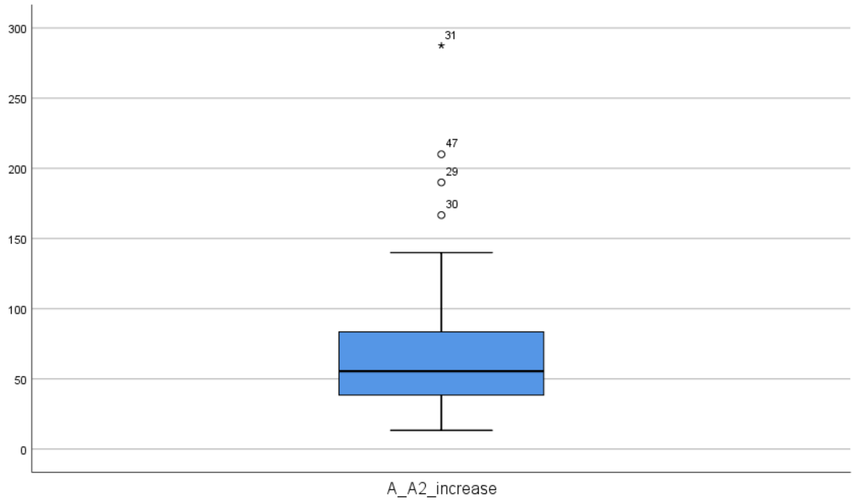

Figure 28. A boxplot on the standard deviation of the percentual increase in degrees A to A2.

The change in the degrees from angles A to A2 was calculated to get a percentual subluxation (Shapiro-Wilk, p=0.000). These percentages were then corrected to get a normal distribution, and the corrected values were compared with other angles and measurements from bones. Interestingly, these subluxation measurements showed a negative Spearman correlation (p=0.011) with the widths of the calcanei (table 8, figure 29). This means that not only the talocalcaneal angle A correlates with the calcaneal widths (see p. 35) on the widest part, but also the level of subluxation on tali affects to the widths.

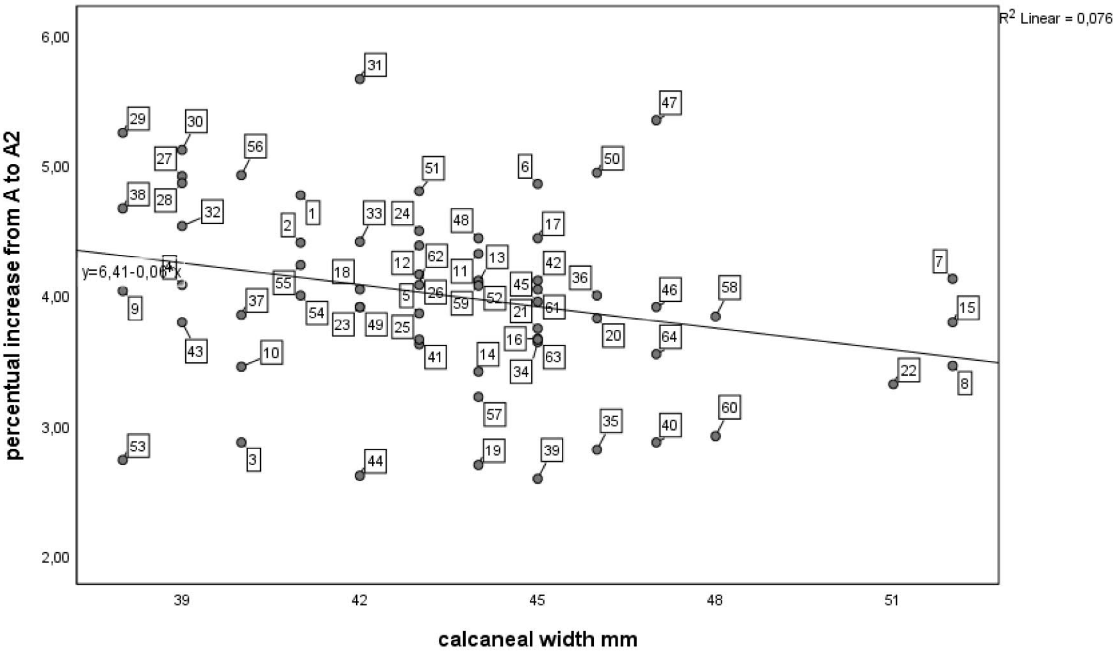

Figure 29. A scatterplot graph of the negative linear correlation between the subluxation of tali (percentual increase from A to A2) and the width of the calcanei.

Table 8. The correlation between the percentual increase from A to A2 and the width of the calcanei.

	N	Pearson r	p	Spearman rs	p
A->A2/Cal. width	64	-0.275	0.028**	-0.315	0.011**

** Correlation is significant at the 0.05 level

A angles showed no correlation between other angles or measurements except with the width of the calcanei explained before (see p. 35). However, the Pearson correlation test between angle A2 and other angles, shows a p=0.038 negative linear correlation (Pearson -0.260) with the angle D (table 9). The figure 30 displays that a bigger extreme talocalcaneal angle indicates a smaller talar head to body angle.

Table 9. The correlation between the angles A2 and D

	N	Pearson r	p
A2/D	64	-0.260	0.038**

** Correlation is significant at the 0.05 level

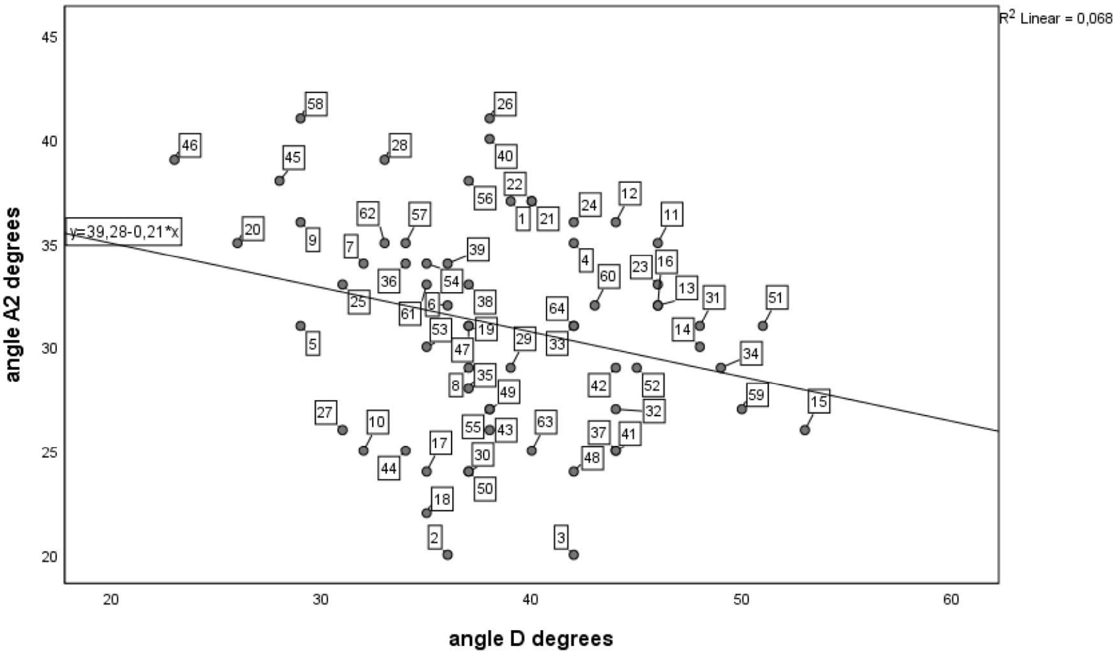

Figure 30. A scatterplot graph of the correlation between the angles A2 (dorsoplantar talocalcaneal) and D (talar head to body).

Strongest correlation between the angles was seen when the angle B (medial talocalcaneal) was compared to the angle E (talar head to body) (figure 31). The angle E values had to be corrected to get a normal distribution. The result for Pearson correlation test shows a statistical significance of p<0.001 with a moderate correlation of 0.524 (table 10). This means that the bigger the talocalcaneal angle is measured from the medial side, the more medially angular the talar head is. In other words, as talus shifts and rotates in a way that the head faces more plantar, the talocalcaneal angle becomes greater. It can be interpreted from the results, that while the talar head faces more plantar after the shift, the head is also more medially angular at the transverse plane.

Table 10. The correlation between angles B and E.

	N	Pearson r	p
B/E	63	0.524	0.000**

** Correlation is significant at the 0.05 level

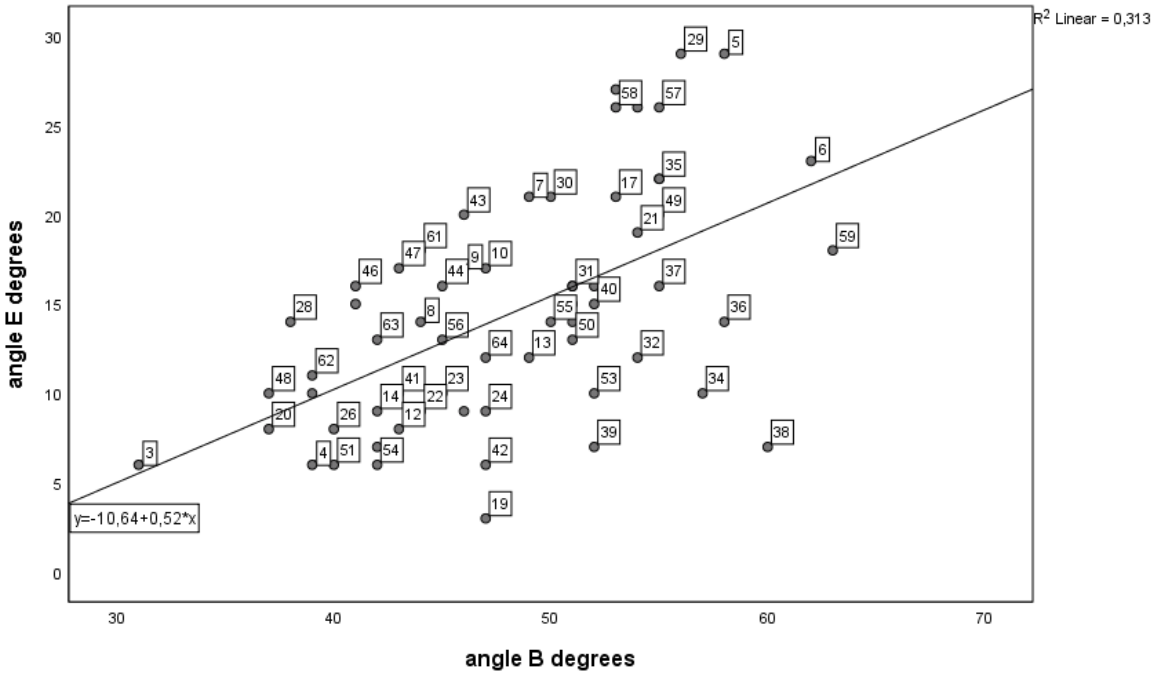

Figure 31. Correlation between angle B (medial talocalcaneal angle) and E (dorsoplantar talar head to body).

Angles A and B are among the most important angles to be measured from radiographs of patients that are suspected to be suffering from pes planus (Lee *et al.* 2005: 83). Interestingly though, they showed no correlation (Pearson, p=0.340) with each other in this study. This might indicate that the increase of a talocalcaneal angle from the dorsoplantar view does not necessarily mean that the talus would have also tilted at the sagittal plane and vice versa.

The result for Pearson correlation test shows a statistical significance of $p<0.001$ with a weak negative correlation of -0.460 between the posterior tibiocalcaneal angle (C) and the dorsoplantar talar head to body angle (E) (table 11, figure 32). This indicates that the more angular the talar head is to talar body, the smaller the tibiocalcaneal angle is. A small tibiocalcaneal angle is caused by calcaneus tilting into valgus and therefore it is considered to be a sign of a flatfoot deformity (Lee *et al.* 2005: 83).

Table 11. The correlation between angles C and E

	N	Pearson r	p
C/E	62	-0.460	0.000**

** Correlation is significant at the 0.05 level

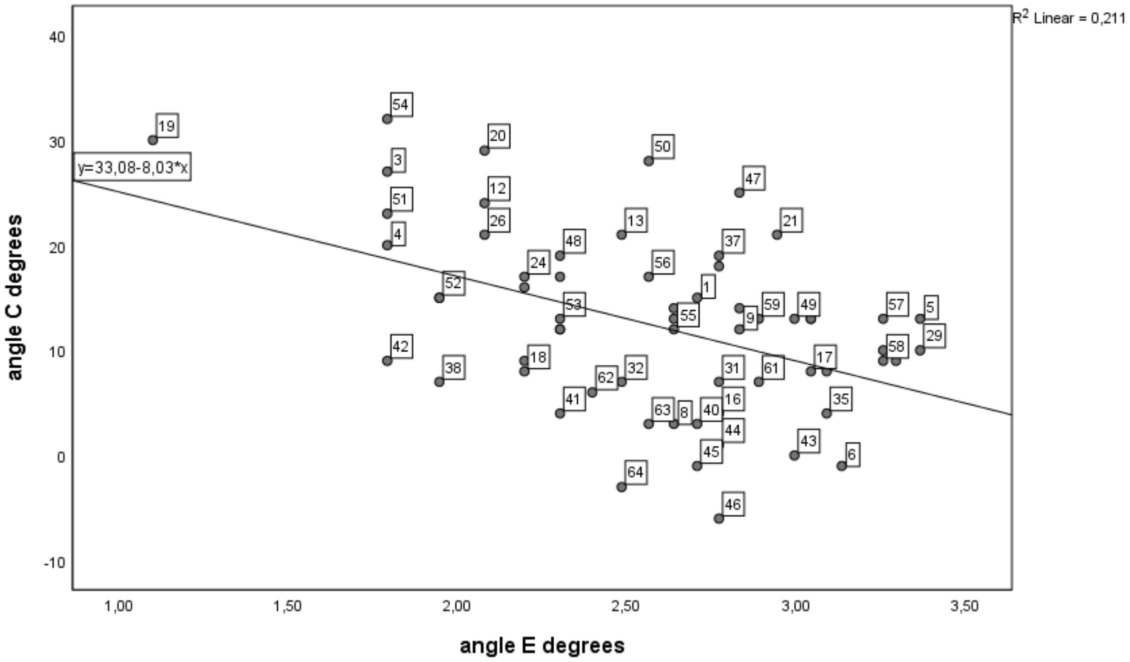

Figure 32. A scatterplot graph on the correlation between angles E and C.

As an addition to the correlations between multiple angles, a slight difference between the right and the left sides was also noted (figure 33). The differences in this result are not big enough to be significant. The sample size would need to bigger to study more of the size differences.

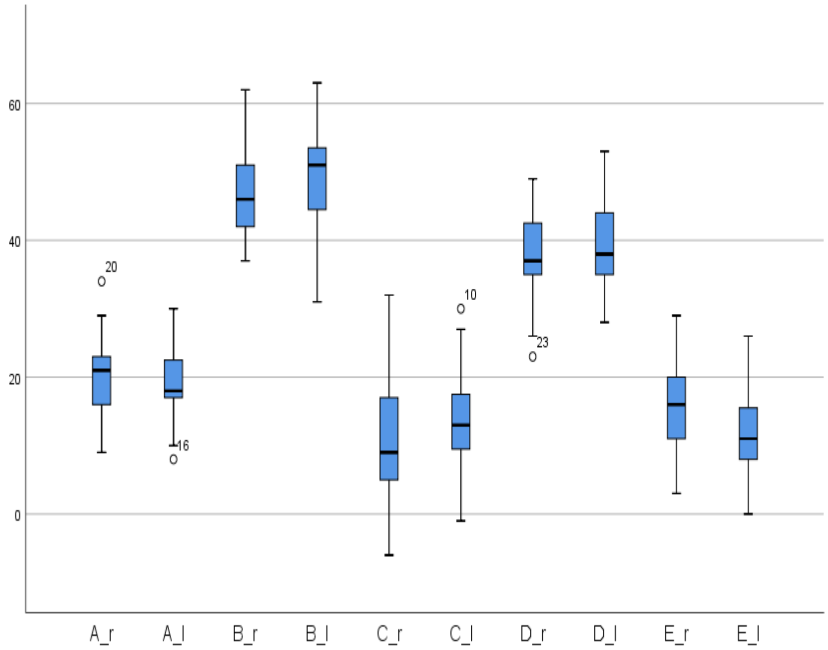

Figure 33. The size differences on angles A-E for both left and right sides.

The height of the individuals (Shapiro-Wilk, p=0.213) has an effect on the angle A2 according to the results. While the height of 28 individuals out of 32 is known, it was possible to use the height as a factor. The Pearson correlation test shows a statistical significance of p=0.033 with a close to weak positive correlation of 0.285.

7. DISCUSSION

The aim of this study was to find a way to diagnose pes planus from skeletal remains. First, it was expected that the sample size would be big enough to include an individual or individuals with prominent flatfoot deformity. Then, it was hypothesized that the deformity would alter the posture of the affected foot. Also, the assumption was that this change in the posture would leave marks on bones. Possibly the shapes of the bones would be different, the relationships between two bones would have changed, or there would be separate morphological changes to be seen.

There were still some critical factors that needed to be considered. Would it be possible to align the bones for the pictures so that the lay outs would stay consistent across the board? In the radiographs, there are ligaments and other soft tissue holding the bones together. Could the results from this study be compared with radiographs? How should these results be interpreted if comparing with the studies of radiographic results would be unreliable?

Tali, calcanei, naviculars and tibiae were measured and pictured for this study, and the pictures were used for angle measurements. These results were then compared with each other to find out if any foot would stand out from the others, or if any specific measurement would indicate a tendency for the flatfoot deformity. Unfortunately though, according to the results the material does not include any individuals with a prominent pes planus. However, there are some interesting correlations in the measurements from the bones and the angles, which would give indications of changes in the bones due to depressed medial longitudinal arches.

First, the results only posed an almost weak correlation (Spearman rs 0.287, $p=0.022$) between the lengths and the widths of the calcanei. Surprisingly, a stronger correlation is found between the angle A (DP talocalcaneal) measurements and the widths of the calcanei (Spearman rs 0.418, $p=0.001$). Second, the angle E (DP talar head to body) correlates significantly with both, positively with the angle B (medial talocalcaneal) (Pearson r 0.524, $p<0.001$) and negatively with the angle C (tibiocalcaneal) (Pearson r -0.460, $p<0.001$).

These results do not unfortunately give a straight answer for the questions of this study. However, what they give, are some new observations on how changes in bones or the altered relationships between bones might affect to other structures around it. The results also offered additional questions which further studies may use in the search of finding a working method for diagnosing the deformity.

TALUS

A used individual indicator of pes planus, the eversion facets[8], were compared to the angle measurements that are most often used in diagnosing pes planus from radiographs. Other than was expected, the results of this study do not support the idea that the angle measurements and the existence of eversion facets would correlate in any way. This finding does not match to other studies on the subject (Darton 2007: 294,296; Martus *et al.* 2008: 2452).

The skeletal material of 32 individuals was used in this study and only nine of them did not have eversion facets on either of their feet. Thus, the frequent existence (55% of all tali) of eversion facets suggests that either there are alternative mechanisms for the development of the facets or that subluxation also occurs without the deformity. In either case, based on these results I would not consider eversion facets as reliable indicators of the flatfoot deformity, but more like normal variation. However, a bigger sample size with cases of prominent pes planus might have shown how particularly larger eversion facets could be connected to the deformity. Martus and colleagues (2008: 2458) noted that males have a higher frequency of eversion facets than females. This is also a factor that might explain the high frequency of eversion facets in this study.

While comparing the height and the width, the tali number 33r stands out as being slightly longer compared to width than the other tali (figure 18). The length of talus has been proven to be longer compared to width and height in flatfeet that in normal feet (Anderson *et al.* 1997: 706). Ponnapula (2012: 320) explains this by stating that a longer talus compared to width dislocates the cyma line more anteriorly (figures 12 and 13). This dislocation adds instability to the talonavicular joint (Ponnapula 2012: 320).

Anderson and colleagues (1997: 707) state that the greater overall length might be due to altered talonavicular coverage as a result of tarsal bone relationship changes. These changes would then cause new bone to form on the talar head and thus increase the

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[8] See page 19.

length of the bone. However, according to them the results are not statistically significant and there is also another explanation for the correlation between increased talar length and pes planus. They note that the shape of the bone might already be shaped longer initially, and only cause symptoms after additional contributing factors have an effect on the height of the arch. The non-correlation is supported by Peeters and colleagues (2013: 284) and Louie and Colleagues (2014: 964–65), who state that the length/width ratio of the tali gives no indication of pes planus. They note that, the previous study might have been lacking due to a sex bias. Therefore, the longer talus compared to width (33r) is only considered as individual variation.

The angle of talar head compared to talar body was measured on two planes, the transverse plane (E) and the frontal plane. The correlation between angles B and E was shown in the results (figure 31). Angle B represents the angle between talus and calcaneus in a medial view, showing the change in the position of tali (figures 12 and 13). Angle E represents the angular position of talar head to body in the transverse plane seen from a dorsoplantar view. This would mean that a bigger talocalcaneal angle, and therefore a more tilted talus, would also mean a more angular talar head compared to body. Probably as talus shifts forward and rotates, the head of the talus adapts and becomes more angular to the body as well.

The tilting of the talus affected with pes planus may also manifest as other changes and not just the differences in the angle measurements. Anderson and colleagues (1997: 707) note that there might be differences in the shapes of the talar heads. According to their study, tali with flatfoot deformity had more oval shaped heads in relation to normal more spherical shaped ones. Peeters and colleagues (2013: 284) also added that, the articular facet on talar head faces more proximal (superior) and the size of the head should be bigger than in the non-flatfeet. Additionally, Louie and colleagues (2014: 964) noted that in symptomatic flatfoot the talar head surprisingly faces more inferiorly. These findings connect because in a foot affected by pes planus, talus would tilt forward, and the head of the talus would face more inferiorly. While the talus shifts, it is natural for the navicular to move more superior. Therefore, the navicular articular facet on talar head would face more superior. However, these aspects were not directly taken into consideration in this study. The shape of the talar head would be more accurate to study from 3D models for example, and there is an indication of the talar head orientation and the tilting of talus in the angle B, D, and E measurements.

The Pearson correlation test showed a statistical significance of p=0.004 between the widths of the talar lateral processes and angle D measurements. The results show that a wider talar lateral process would therefore indicate a more angular talar head (frontal plane) and vice versa. However, the correlation is also seen between angle A2 and D measurements (Pearson r -0.260, p=0.038), which indicates that the wider subluxation on tali also means a less angular talar head to body (D). Still there is now correlation between the A2 and the widths of the lateral processes. This could mean that a more angular talar head would develop with a wider lateral process or develop due to larger degree of subluxation. Alternatively, a more angular talar head could drive the talus to subluxate more or develop a wider lateral process. Still the width of the lateral process and the subluxation of the talus might as well exist without the other.

CALCANEUS

According to table 5, the length of calcanei only correlates with the width on a 0.05 level (Spearman rs 0.287). This result is interesting, because there is a lot of variation in the widths, but it is uncertain if they should correlate more strongly with the lengths. If there would be no changes in the surrounding bones or structures affecting to the shape of the calcanei, there should be a significant correlation between the measurements. Therefore, there must be an additional factor influencing to the lengths.

There is also correlation between the angle A and the width of the calcanei (Spearman rs 0.418, p=0.001). Therefore, a wider calcaneus could be considered as a sign of a shifted talus. The sustentaculum tali might adapt to a change in the position of a talus, or the wider calcaneus might push the talus to shift. The position of the talus could affect more on the width of the calcaneus (P<0.01), than the length of the calcaneus does (P<0.05). While the angle A and the width of the calcanei correlate, there is no correlation between the widths and the angle C measurements (p=0.191, Pearson -0.167). Thus, these results suggest that the morphology of the calcaneus is affected by outside factors. Therefore, the results of this study do indicate that the location and the changes in tali have a bigger effect to the widths of the calcanei than do the lengths of the calcanei or the position of them. Alternatively, the results might be interpreted in a way that the wider calcanei affect more to the position of the tali than they do to the position of the calcanei itself.

The position of calcaneus relative to tibia is also affected by pes planus. Kitaoka and colleagues (1998: 448) found out that there was a substantial difference in the calcaneal position relative to tibia. Van Boerum and Sangeorzan (2003: 423) explained that a depressed arch causes the calcaneus to subluxate posteriorly. This subluxation weakens the support that the anterior process of calcaneus has on the head of talus (Van Boerum & Sangeorzan 2003: 423). This is seen in the medial pictures and angle B measurements, where the position between talus and calcaneus is compared (figure 11).

Thus, if there is posterior drifting of the calcaneus which causes the talus to plantar flex, does calcaneus evolve wider to better support changed position of talus? The reason behind this might be a law called Wolff's Law[9], or more simply bone functional adaptation (Ruff *et al.* 2006: 485). However, the results in this study did not show any correlation between the measurements of lateral talocalcaneal angle (B) and the width of the calcaneus. This actually supports the hypothesis that the calcaneus has developed wider to support the talar head and prevent the tilting of talus. The talocalcaneal angle (A) might be bigger in the dorsoplantar view, but owing to the better support of wider calcaneus, talus has not tilted, and the increase of the talocalcaneal angle is not showing in the later view.

NAVICULAR

As the results of this study indicated, the size of talar articular facets on proximal naviculars do not correlate with any other measurements except the size of naviculars. As Louie and colleagues (2014: 962–64) have noted, this might be due to the orientation change in naviculars, and how the bones still maintain contact with tali, except in extreme cases. They studied the changes of talonavicular joint (TNJ) in pes planus and note that the orientation might change, but the overall coverage stays the same. What they found out was that naviculars were more medially aligned in the control group than symptomatic pes planus. They also state that how navicular articulates with talus, is the most indicative measurement of painful pes planus.

This does not however rule out the correlation between navicular cup depth and pes planus, which was studied by Peeters and colleagues (2013: 286). According to them, the depth of articular facets was deeper in naviculars with pes planus. They also noted that the height of the navicular cups was bigger, which together with the deeper cups

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[9] The appearance of bone remodeling due to adaptation to mechanical loading. (Ruff *et al.* 2006: 484)

means that the coverage does not decrease in pes planus, it only shifts. This shift of talonavicular joint coverage is better studied from 3D pictures for example and did not fit into this research unfortunately.

ANGLES

There was also a moderate correlation (Pearson r 0.524, p<0.001) between the angles when comparing angles B and E. While talus has shifted more plantar and the head tilted downwards (B), it is natural that the head becomes more medially angular (E) as well to adapt to the change. Or maybe the more angular shape of the talar head made the plantar tilting possible for talus. The angle E also negatively correlates with the angle C (Pearson r -0.460, p<0.001). Thus, meaning that calcaneus in valgus affects to the angular shape of the talar head as well. Angles B (talocalcaneal) and C (tibiocalcaneal) are among the most important measurements for diagnosing pes planus from radiographs (Lee *et al.* 2005: 83). Therefore, having the angular shape of the talar head measurements correlate to these angles emphasizes the importance of talar head position in pes planus.

There were clear indications in some of the bones that the talocalcaneal joints might have subluxated causing wider facets. Subluxation was measured by calculating the percentual change from the angles A to A2. These measurements however, can only be used as directional. While using the bones without the connective tissues, and reconstructing the weight bearing positions, the results are only approximate.

Subluxation has been studied to take place during weight-bearing in the talocalcaneal joint of feet with pes planus (Ananthakrisnan *et al.* 1999: 1151). Ananthakrisnan and colleagues state that anterior and middle facets subluxate more than posterior facets (table 8). The study was conducted by observing the surface areas of facets between tali and calcanei as well as the overlapping areas. Their results were significant because they offered additional knowledge on the changes of one of the central joints in the development of an acquired pes planus, the talocalcaneal joint.

Table 8. The percentages of the areas that are not overlapping and are considered subluxated. Based on the study of Ananthakrisnan and colleagues (1999: 1151).

	Flatfoot	Control
Calcaneus posterior f.	32%	8%
Calc. anterior & middle f.	49%	5%
Talus posterior f.	30%	11%
Talus anterior & middle f.	56%	13%

In this study, the approximate results of subluxation were compared to other angles and measurements. As the results showed, there exists a weak negative correlation between the subluxation and the calcaneal widths (Spearman rs -0.315, p=0.011). This would indicate that a bigger percentual increase in the angles from A to A2 means a narrower calcaneus. However, as mentioned before, the percentual increase values from A to A2 should only be used as approximate results to indicate subluxation.

The mean of the angle B measurements is 48 degrees. According to Van Gestel and colleagues (2015: 180), the range that is considered normal for lateral talocalcaneal angle in radiographs is 25-45°, thus meaning that the degrees over 45 would mean hindfoot valgus and flattening of the arch. However, angle B measurements which reflect the talocalcaneal angle, are taken from bones adjusted into a medial view and therefore are not fully comparable with the findings of Van Gestel and colleagues. There was also a difference in the measuring guidelines. They measured the talocalcaneal axis as a line intersection talus. In this study, the axis was drawn along the superior surfaces of talar body and head. Therefore, the angular position of talar head might have had some effect on the angle B measurements.

Van Gestel and colleagues (2015: 180) also set a range for the normal degrees of the dorsoplantar talocalcaneal angles (angle A). According to them, the degrees 15 to 30 are considered normal, while everything over 30° are considered to be connected to a depressed arch. There is only one foot in this study that has the angle A big enough to be considered a hindfoot valgus by Van Gestel and colleagues. This is the left foot of an individual number 147 and the degree is 34. However, it needs to be remembered, that drawing straight lines from results that were collected from radiographs should be done with caution. There is also the difference in weight bearing, which cannot be reliably simulated on bones. Still, this individual number 147 had the widest talocalcaneal angle A in their left foot, which stood out from the rest on the material and might indicate pes planus.

Interestingly yet, the angles A and B do not correlate with each other according to the results. Therefore, it can be assumed that a medially shifted talus at a transverse plane might get additional support from calcaneus and the wider sustentaculum tali. The correlation might only show on the prominent cases, which this material did not include. The prominent cases would probably show that the support of the calcaneus has failed, and the talus has tilted.

The heights of the individuals were used as additional factors. The height affects most on the angle A2 measurements according to the results ($p<0.05$). This indicates that if a person is taller, their tali would also have more subluxation, which would indicate lowering of the medial longitudinal arch. Tenenbaum and colleagues (2013: 814) came to a different conclusion in their study. According to them, shorter height on both males and females adds the frequency of pes planus. The difference in these results is interesting and should be studied on a larger sample. However, the wider angle A2 does not directly indicate pes planus and neither is the sample size big to make any definite conclusions. Thus a bigger sample size would be needed to argue against the results of Tenenbaum and colleagues (2013: 814). Additionally, there are some side differences in the data, but this might be due to a small sample size. A bigger sample would be needed to make assumptions on if the situation of a stronger versus a weaker foot would explain the difference for example.

IN GENERAL

Unfortunately, a study like this cannot give any answers on the sequence of the changes in the deformity. The changes expressed in the results might have developed due to pes planus, or the medial longitudinal arch might have lowered due to originally misshapen bones. Additionally, there is a lot of normal variation present. If there was imbalance in muscles and tendons, PTT insufficiency for example, changes in the bones were probably caused by an adaptation (Louie *et al.* 2014: 965). However, from bones alone, it is very difficult to say what the driving force was. In most cases, we can only observe the outcome.

There are also some shortcomings in the process that need to be noted. There is a wide range of individual variation in pedal bones, which complicates the determination of the reference points. No matter how precisely the points are set, measuring bones always includes a certain degree of observer error. However, there results were handled as groups and no single measurement was given a great significance. Therefore, a slight change in a single measurement due to observer error would not change the significant correlations.

The reference measurements from other studies had mostly used radiographs instead of only bones. Therefore, the effect of tendons, ligaments, and other connective was noted while making comparisons. Thus, this study focused on angle-to-angle and angle-to-bone-measurement correlations more than the correlations of angle degree measurements from other studies.

Even though we are only able to observe the outcome, it gives good knowledge on what the endpoint of pes planus looks like, and what changes have happened compared to the normal height medial longitudinal arches. These results may then be used in multiple relations from medical cases to footwear industry. Thus, what does this research offer to the field of studying pedal health and pes planus?

The results show that the widths of the calcanei have a significant influence on the position of the tali. The position of the tali seems to be depending on the width, and therefore the support, of the calcaneus on the sustentaculum tali. The angular position of the talar head in the transverse plane is also a good indication of a tilted talus and a lowered medial longitudinal arch. Conflicting to previous studies, these results showed no correlation with the existence of the eversion facets and the angles. Also the correlation with pes planus and the height of the individuals was opposing to the study by Tenenbaum and colleagues (2013: 814). However, the sample size here is smaller and there are unfortunately no prominent pes planus cases seen in the material.

The prevalence of pes planus patients nowadays indicated that the research material should have also included some individuals with the deformity. Interestingly, no cases with prominent flatfoot deformity were observed. This might show that the condition was not as common decades ago as it is now. Maybe the shoes that are worn nowadays have a negative effect on pedal health. However, the assumption is in need of further research.

This study does not offer a simple method for diagnosing pes planus. What it offers however, are interesting points on the relationship between tali and calcanei, and the influence that they have on the depressed medial longitudinal arches. Measuring angles between bones in diagnosing pes planus cannot be proven as a reliable method based on this research, but neither can it be dismissed as unreliable. To make definite conclusions in a further research, these questions would need a larger study material that includes individuals with noticeable flatfoot deformities. Larger collections from other countries could be utilized in doing that.

8. CONCLUSIONS

For a deformity as common as pes planus, it is very poorly studied from bones. The biomechanics of feet are well known, but there is a lot of individual variation which sometimes makes drawing straight lines between results hard, if not impossible. It appears already from the start, that pes planus is nothing but individual variation. There are many levels to the condition, which can be either symptomatic or asymptomatic. Other people might live with a prominent depressed medial longitudinal arch for their whole life and never suffer from symptoms, while others get pain on their knees, hips, and shoulders from the tiniest unbalance of their feet. The defining of the deformity is especially hard when the causes of the problem, symptoms, and the effects are as diverse as in pes planus.

This research concentrated on how the flatfoot deformity manifests on bones. As the relationships between bones change, the changes affect the bones in question. This is explained by Wolff's law of bone remodeling (Ruff *et al.* 2006: 484). However, how do we know if the change happened as a result or was it the original cause? The simple answer is that we do not know. Therefore, this research focused on the end result seen in the bones.

After the measurements and the pictures of the bones were taken, the data was analyzed. It shows some interesting correlations between the angels and the morphology of the bones. The width of the calcaneus indicates more importance on the medial longitudinal arch collapse than is previously highlighted. The angular shape of the talus head on the transverse plane also stands out as a significant change. Additionally, conversely to the study of Darton (2007: 294,296), this study shows no correlation on the angle degrees and eversion facets. In other words, the positions of the bones in this study have no effect on the prevalence of eversion facets. This might be due to the sample size however.

Finally, could something have done differently? There are a couple of measurements that could have been taken in another way to make them more exact and accurate. The coverage of the talonavicular joint was measured using the percentual coverage of the talar head articular facet on navicular compared to the overall size of the proximal navicular. However, probably a more precise way could have been to measure the depth of the articular facet. Another measurement that would have added to the study would have been the orientation of talar head from the medial perspective. This would tell if a more superiorly oriented articular facet (Peeters *et al.* 2013: 284) would also mean a difference in the orientation of talar head in general. This plantar shift of tali affected by pes planus is indicated by Louie and colleagues (2014: 964).

In a future study, these measurements could be taken from 3D models of bones. This would make later observations of the bones a lot easier. Also, a bigger sample size would be needed in order to make any definite conclusions. The sample size on this study could have been so small that there simply were no advanced flatfoot deformities on these individuals.

Future possibilities to apply the methods of diagnosing pes planus are extensive. The main focus that paleopathology aims for, is to know more on the pathological conditions and the health of past populations. In addition to the knowledge on pedal health of our predecessors, paleopathological research would also give suggestions into the wellbeing of our offspring. Therefore, more research is needed to find out how common pes planus was on past populations. The prevalence of the deformity should also be compared between past populations who take part on diverse activities wearing different kinds of shoes or going barefoot.

The studies of pes planus and the depressed medial longitudinal arches could be extended to as far as to the fossilized remains of our ancestors. The better knowing of biomechanics of the feet affected by pes planus, could give more insight into the research of the evolution of bipedalism and to the development of the arches in the first place. By knowing the proximate mechanisms behind pes planus, the research is also able to focus more on the ultimate questions behind the arches of the feet. Why did hominins adapt to bipedalism? Why did bipedalism cause their medial longitudinal arches to develop? Also, because the medial longitudinal arches developed for a significant task in biomechanics, why are there still so many peoples affected by this condition? Was there less of the condition before, and it is only now getting more common due to the way we walk and run, estranged from the original way? There are so many questions still left unanswered.

Another branch that would benefit from the knowledge of how pes planus manifests on bones, is forensic anthropology. Pes planus is a deformity that while being prominent, will show to the people around you. In most cases, it even shows from the way the person’s shoes are worn. Knowing that the skeleton forensic anthropologists are trying to identify was suffering from a flatfoot deformity, might help in coming up with a positive identification.

Lastly, even though a simple method of diagnosing pes planus from bones still have not been found, there are once again more indications on how it manifests on bones. Additional research with a broader sample size should make the indications of pes planus more clear. After that, the possibilities to study pes planus in archaeological or paleoanthropological contexts are endless.

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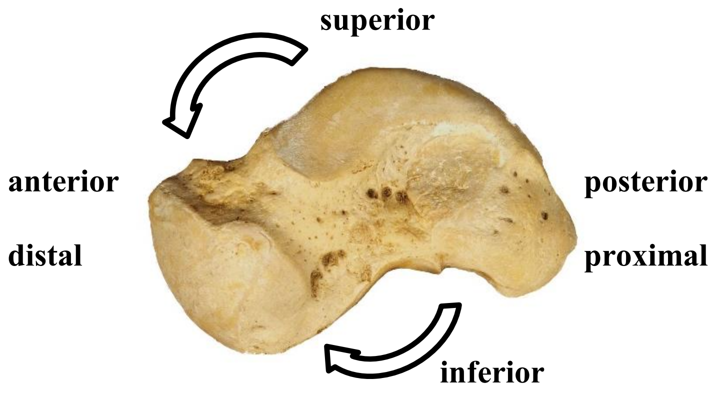
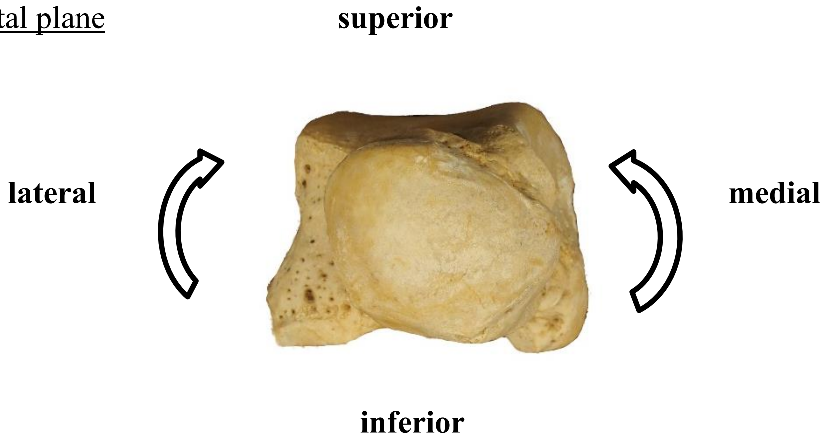
Appendix 1: Planes

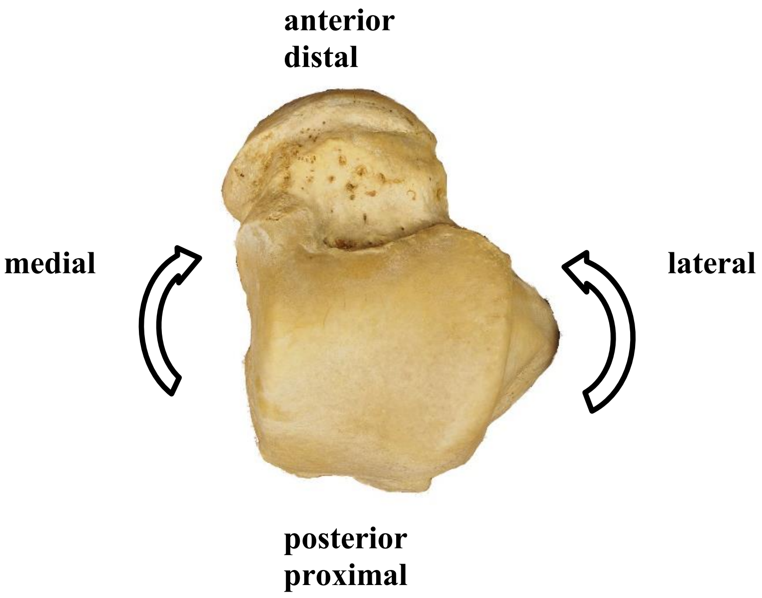
Sagittal plane



Frontal plane



Transverse plane



Appendix 2: List of Individuals

SPSS #	ID
1	6r
2	6l
3	17r
4	17l
5	20r
6	20l
7	26r
8	26l
9	27r
10	27l
11	29r
12	29l
13	31r
14	31l
15	33r
16	33l
17	77r
18	77l
19	83r
20	83l
21	84r
22	84l
23	114r
24	114l
25	116r
26	116l
27	119r
28	119l
29	124r
30	124l
31	126r
32	126l

SPSS #	ID
33	128r
34	128l
35	145r
36	145l
37	146r
38	146l
39	147r
40	147l
41	148r
42	148l
43	149r
44	149l
45	153r
46	153l
47	155r
48	155l
49	167r
50	167l
51	1704r
52	1704l
53	1709r
54	1709l
55	1713r
56	1713l
57	1714r
58	1714l
59	1719r
60	1719l
61	1720r
62	1720l
63	1722r
64	1722l

Appendix 3: Eversion Facets on Tali

ID	length	width
6r	15	7
6l	13	5
17r	13	3
17l	13	4
26r	10	3
26l	9	3
27l	10	5
29r	12	5
29l	14	5
77r	9	3
77l	9	4
114l	6	4
116r	15	5
116l	11	5
119r	11	7
124r	15	3
126r	7	4
128l	11	5
147l	6	3
148r	10	2
149r	7	3
149l	6	4
155r	11	7
155l	9	5
167r	bad preservation	bad preservation
167l	bad preservation	bad preservation
1704r	10	7
1704l	14	10
1714r	8	5
1714l	8	5
1719r	7	4
1719l	8	5
1720l	14	4
1722r	12	4
1722l	12	7

Appendix 4: Strength of Correlation

Natural science

Coefficient value	Strenght of association
0.3<= r <0.5	weak
0.5<= r <0.7	moderate
0.7<= r	strong

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TUOMISALO, LAURA: A Paleopathological Analysis to Identify Possible Adult Flexible Pes Planus from Pedal Bones

Pro gradu -tutkielma, 61 sivua, 4 liitettä
Arkeologia
Huhtikuu, 2019

Lyhennelmä (summary in Finnish)

Lättäjalkaisuus on viime aikoina herättänyt paljon keskustelua. Joidenkin mielestä se on sairaus, joka vaatii korjausta ja jopa leikkaushoitoa. Toisten mielestä lättäjalkaisuuden aiheuttamat muutokset jaloissa ovat vain osa yksilöllistä vaihtelua. Näiden ääripäiden välistä löytyy kuitenkin ryhmä, joka uskoo siihen, että lättäjalkaisuudesta voi parantua jalkojen pieniä lihaksia treenaamalla. Historiallinen näkökulma antaisi tähän keskusteluun tietoa siitä, miten erilaiset kengät ovat mahdollisesti jalkoihimme vuosisatojen aikana vaikuttaneet.

Madaltunutta sisempää pitkittäistä jalkaholvia pidetään merkkinä lättäjalkaisuudesta (*pes planus*). Korkeita jalkaholveja pidettiin ennen aristokraattisen kauniina ja tämä on saattanut osaltaan vaikuttaa siihen, että lättäjalkaisuutta pidettiin vielä pitkään sairautena, joka vaati aina hoitoa. Ennen luultiin myös, että pes planus saattaa kehittyä, jos esimerkiksi lapsena seisoo pitkään pystyssä. Nykyään tiedetään, että tämä ei pidä paikkaansa ja pes planus nähdään monesti vain yksilön ominaisuutena, jos madaltunut holvikaari ei aiheuta kipua.

PES PLANUS

Lättäjalkaisuus eli pes planus jaetaan joustavaan ja jäykkään kategoriaan. Jäykkä lättäjalka johtuu monesti rakenteellisesta poikkeamasta, joka usein huomataan jo lapsena. Joustava lättäjalka taas saattaa johtua hyvin monesta asiasta, joita ei useinkaan pystytä havaitsemaan osteologisesti. Näitä saattaa olla muun muassa jänteiden löysyys, tiukka kantajänne tai takimmaisen säärilihaksen jänne.

Lapsilla on syntyessään matalat jalkaholvit, jotka kehittyvät iän myötä. On kuitenkin löydetty muutamia altistavia tekijöitä siihen, että jalkaholvit eivät kehitykään kuten kuuluisi. Lättäjalkaisuuden yleisyyteen vaikuttaa sukupuoli (yleisempää miehillä), pituus (yleisempää lyhyemmillä), sekä suurempi BMI lukema.

Yksinkertaisimmillaan voidaan ajatella, että jalkaa tukeville rakenteille tulee liian suuri rasitus, jota jalan holvikaari ei jaksa kannatella ja madaltuu. Tämä saattaa aiheuttaa muutoksia luissa ja luiden välisissä suhteissa. Tässä tutkimuksessa selvitetään juuri näitä muutoksia, vertailemalla miten eri kulmamitat ja luista otetut mitat korreloivat keskenään. Tavoitteena on kehittää menetelmää, jolla lättäjalkaisuuden diagnosoiminen onnistuisi pelkän luumateriaalin avulla.

MENETELMÄT

Kun lättäjalkaisuutta diagnosoidaan eläviltä ihmisiltä, apuna käytetään sekä röntgenkuvia että fyysistä tutkimusta. Fyysinen tutkimus osoittaa madaltuneen holvikaaren, taittuneen jalkaterän sekä kääntyneen kantapään. Osteoarkeologit pystyvät kuitenkin ainoastaan tutkimaan luustoa.

Tässä työssä tutkitaan kolmea nilkan luuta. Telaluu (*talus*), kantaluu (*calcaneus*) ja veneluu *(os. naviculare)* tutkitaan tarkemmin ja sääriluuta (*tibia*) käytetään kuvissa oikean asennon saamiseksi. Nämä kolme jalkapöydän ja nilkan luuta ovat jalan luista parhaiten edustettuina materiaalissa ja niiden asento on yleisimmin tarkasteltavana, kun lättäjalkaisuudesta tehdään kliinisiä diagnooseja. Tässä tutkimuksessa luut kuvataan asetettuina luonnollisiin anatomisiin asentoihin yhdessä viereisen luun kanssa. Kuvaamisen jälkeen kuvista analysoidaan luiden väliset kulmat, joita vertaillaan keskenään. Kulmat ovat samoja, joita käytetään röntgenkuvista diagnosoimiseen.

Telaluu sijaitsee jalkaterän liikkeiden kannalta merkittävässä paikassa, sillä se on osa kumpaakin niveltä, jotka muodostavat nilkan. Telaluista mitattiin pituus isovarpaan pitkän koukistajan jänteen uurteesta, kokonaisleveys, sekä korkeus. Lisäksi luiden sivu-ulokkeiden korkeus ja leveys mitattiin. Mikäli luusta erottuivat *eversion facetit*, niiden koko mitattiin myös. Nämä nivelpinnat muodostuvat telaluun takimmaisen kantaluunivelpinnan ja kantaluun nilkkapuokaman (*sinus tarsi*) jatkuvasta kontaktista.

Kantaluusta tehdyt mittaukset olivat kokonaispituus, sekä leveys kahdesta kohtaa. Kantaluun leveys mitattiin, koska hypoteesina on, että telaluun subluksaatio saattaa aiheuttaa kantaluun telaluunkannattimen (*sustentaculum tali)* leventymistä. Veneluusta mittatiin kokonaispituus ja kokonaisleveys, mutta myös veneluun telaluunivelpinnan pituus ja leveys. Tämä mahdollistaa nivelpinnan koon vertaamisen luun kokoon.

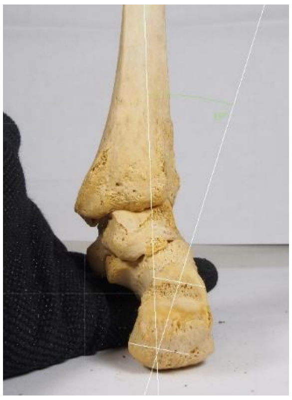
Kun mittaukset oli tehty, luut kuvattiin ja kuvista dokumentoitiin viisi kulmaa. Kulmat A ja A2 mitattiin yläkuvista ja niissä mitattiin telaluun ja kantaluun välistä kulmaa.

Kulmissa B mitattiin myös telaluun ja kantaluun välistä kulmaa, mutta mediaalikuvista. Kulmat C mitattiin takaapäin otetuista kuvista ja kulmissa D sekä E mitattiin telaluun pään asentoa muuhun osaan.

Kulma A (kuva 1.) osoittaa telaluun ja kantaluun välisen kulman suuruuden. Luut asetettiin niiden luonnollisille paikoille, niin että telaluun sääriluunivelpinta oli takaa päin vatupassilla katsoen suorassa. Kulma A2 osoittaa samaa kulmaa, mutta niin että telaluu on käännetty siihen ääriasentoon, johon se nivelpintojen mukaan luontevasti kääntyy. Myös kulma E (kuva 2.) mitattiin samoista ylhäältäpäin otetuista kuvista. Tämä kulma osoittaa sitä, miten telaluun pää on sijoittunut verrattuna telaluun muuhun osaan. Kulman E lisäksi kulma D mittaa telaluun pään asentoa. Tämä kulma mitattiin distaalikuvista (kuva 3.)

Kuvat 1, 2 ja 3. Vasemmalla kulma A osoittaa telaluun ja kantaluun välisen kulman, sekä keskellä kulma E osoittaa telaluun pään asennon verrattuna muuhun osaan. Lisäksi oikealla on kuva kulmasta D, joka myös osoittaa taluksen pään kulmaa verrattuna muuhun osaan luuta, mutta tämä kuva on otettu luun distaalipuolelta.

Kuva 4. Kulma B mitattuna mediaalipuolelta.



Kuva 5. Kulma C mitattuna takaapäin.

Kulma B (kuva 4.) osoittaa mediaalikuvista kantaluun ja telaluun välisen kulman. Luun oli helpompi asettaa johdonmukaisesti mediaalipuoli ylöspäin ja siksi tämä puoli on kuvattu. Lisäksi nilkasta otettiin kuva takaapäin, jolloin sääluuta käytettiin nilkan asennon hahmottamisessa. Näistä kuvista mitattiin kulma C (kuva 5.), joka osoittaa kantaluun asentoa verrattuna sääriluuhun.

Röntgenkuvista mitattujen kulmien suuruuksia käytetään summittaisesti tämän tutkimuksen tulosten vertailuun. Suoraa vertailua ei voida tehdä, koska röntgenkuvien asentoihin vaikuttavat lisäksi sidekudos ja pehmytkudos. Aiempaa tutkimusta, jossa jalan luita oli tutkittu tällä tavoin, ei löytynyt. Tästä johtuen sellaista vertailuaineistoa ei käytetty.

MATERIAALI

Tutkimuksen materiaalina käytettiin Helsingin yliopiston ihmisluukokoelmaa, joka sijaitsee Luonnontieteellisessä museossa. Tämä kokoelma on Suomen laajin ja parhaiten säilynyt. Kokoelman sarja A sisältää 201 yksilöä, joiden henkilöllisyydet, sukupuolet ja usein myös ammatit ovat tiedossa. Lisäksi pituus ja kuolinikä on monen kohdalla merkitty. Luut ovat tulleet kokoelmaan vankiloista, sairaaloista ja vanhainkodeista. Ne on kerätty 1900-luvun alkupuolella ja olleet opetuskäytössä ennen päätymistään kokoelmaan.

Sarja A sisältää 32 luurankoa, jotka olivat säilyneet riittävän hyvin tutkimusta varten. Materiaalina käytettiin siis 64 jalan luustoa. Näistä yksilöistä yksi oli nainen ja muut miehiä. Heidän ikänsä olivat 17 ja 77 vuoden väliltä ja pituutensa 156 cm ja 182 cm väliltä.

TULOKSET

Telaluun pituuksia ja leveyksiä verrattiin keskenään, jolloin huomattiin, että telaluu numero 33 erottuu muista hieman pidempänä verrattuna leveyteen. Kulma D myös osoittaa pientä negatiivista korrelaatiota kulman E kanssa. Tämä tarkoittaisi, että telaluun pään ollessa isommassa kulmassa transversaalitasolla, on se pienemmässä kulmassa frontaalitasolla. Tämän lisäksi eversion facetit löytyi 35 telaluusta, mutta niiden olemassaolo ei osoittanut mitään korrelaatiota kulmamittausten tai luista otettujen mittojen kanssa.

Kantaluiden leveydet osoittivat yllättävän pientä korrelaatiota pituuksien kanssa. Silti ne osoittivat vahvaa korrelaatiota kulmien A kanssa. Tämä viittaisi siihen, että telaluun asennolla on kantaluun pituutta suurempi vaikutus kantaluun leveyteen.

Veneluiden telaluunivelpintojen koolla ei ole korrelaatiota muiden mittausten kanssa kuin veneluun koon. Tästä voidaan päätellä, että telaluun asennon muutoksella ei ole merkitystä nivelpinnan kokoon. Veneluu vain mukautuu telaluun asennon muutokseen, mutta nivelpinnan koko ei muutu.

A2 kulma osoittaa negatiivista korrelaatiota kulman D kanssa. Tämä viittaa siihen, että suurempi telaluun ja kantaluun välinen kulma tarkoittaisi pienempää telaluun pään kulmaa frontaalitasolla. Voimakkain korrelaation on kuitenkin nähtävissä kulmien B ja E välillä. Tämä tarkoittaisi sitä, että mikäli telaluun ja kantaluun välinen kulma on suurempi, telaluun pää on myös suuremmassa kulmassa transversaalitasolla.

A ja B kulmat ovat tärkeimmässä asemassa, kun pes planusta diagnosoidaan kliinisesti. Kuitenkaan, tämän tutkimuksen mukaan nämä kulmat eivät osoita mitään korrelaatiota keskenään. Kulmat C ja E taas osoittivat vahvaa negatiivista korrelaatiota keskenään. Tämä viittaa siihen, että mitä suurempi telaluun pään kulma on transversaalitasolla, sitä pienempi kantaluun ja sääriluun välinen kulma on. Näiden tulosten lisäksi lievä ero on nähtävissä kulmamittauksissa oikean ja vasemman jalan luiden välillä. Tämä voi kuitenkin selittyä pienellä aineistolla.

POHDINTA JA PÄÄTELMÄT

Eversion nivelpintojen laaja esiintyvyys aineistossa on aiemman tutkimustuloksen kanssa päinvastainen. Nämä nivelpinnat on aiemmin tulkittu nimenomaan lättäjaloista kertoviksi, mutta tämän tutkimuksen mukaan niiden laaja esiintyvyys ja korreloimattomuus muiden mittausten kanssa viittaa siihen, että ne ovat enemmänkin yksilön ominaisuus.

Kantaluun leveyden ja telaluun asennon suhde on mielenkiintoinen. Kantaluun leveydet näyttäisivät tulosten perusteella korreloivan vahvemmin telaluun asennon kanssa, kuin kantaluiden pituusmittausten kanssa. Tämä viittaisi siihen, että ulkopuolinen voima, kuten telaluun asennon muutos, vaikuttaisi kantaluun leveyteen, eikä ainoastaan se, kuinka pitkäksi luu kasvaa.

Tämänlaisen tutkimuksen heikkoutena on se, ettei se pysty tarjoamaan tietoa lättäjalkaisuuden syistä. Luiden perusteella on lähes aina mahdollista tutkia ainoastaan lopputulemaa. Tämän tutkimuksen tavoitteena oli kehittää menetelmää, jolla lättäjalkaisuutta voisi diagnosoida luuaineistosta. Valitettavasti tämän tutkimuksen tulokset eivät kuitenkaan tarjonneet yksiselitteistä menetelmää tähän. Tulokset kuitenkin antoivat viitteitä siitä, että kantaluun leveydellä saattaisi olla suurempi merkitys jalkaholvin madaltumiseen kuin on aiemmin tutkittu.