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The Clinical Anatomy of the Hallucal Sesamoids and their Attachments

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Abstract

The hallucal sesamoid bones are essential, but poorly understood, features of the first, or great, toe complex. With the associated structures of the foot, collectively termed the first ray, this complex is essential for optimal foot function. Disorders of this region present symptomatically in a broad range from intermittent discomfort through to a complete inability to walk or weight-bear. Pain in this region may also be enough to interrupt sleep and a range of daily tasks. Given the perceived importance of the hallucal sesamoids to this complex, it is perhaps surprising to discover the anatomy of the hallucal sesamoids, and particularly their interaction with neighbouring tissues, is poorly understood. One major consequence of this is the lack of a clear, consistent anatomical foundation for the diagnosis, treatment (including surgically) and management of these disorders. This thesis will document a series of studies which aim to collectively enhance the anatomical understanding of the hallucal sesamoids and their relations.

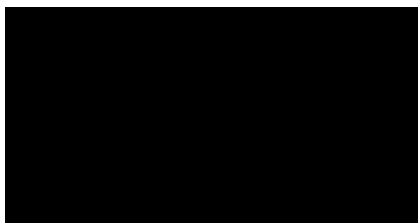
After exploring the historical context of the hallucal sesamoids, reviewing the current anatomical and clinical literature, and establishing some key concepts about the presence, absence and variability of these bones, a series of detailed studies will be presented. Using a multi-modal approach that includes dissection, 3D modelling, medical imaging and sectional anatomy (macro and micro), the key tissues thought to interact with the hallucal sesamoids will be investigated: the adductor and abductor hallucis muscles, the plantar aponeurosis, the flexor hallucis brevis muscle and a range of highly specialised ligaments. The ligaments include the deep

transverse metatarsal and sesamophalangeal, , amongst others, along with interactions with other tissues such as tendon tunnels, plantar plates and joint capsules. Of particular importance when considering the function of these structures is their attachment to skeletal tissues, such as the hallucal sesamoids. There is contention over what tissues are attached to each of the two hallucal sesamoids. These studies provide a detailed, quantified and uniquely visualised account of the attachments to each bone, and to neighbouring structures. This comprehensive account provides a strong basis for the development of more anatomically informed diagnostic approaches and clinical management of disorders of this area.

The key findings presented in this thesis include definitive three-dimensional mapping of the detailed attachments to each hallucal sesamoid. These dispel common misconceptions that the sesamoids are engulfed by a single tissue, or that they do not have substantial connections to a range of structures. These data strongly demonstrate these sesamoids have multi-directional interactions which maintain their dynamic position through the gait cycle, but are also particularly vulnerable to injury, including iatrogenic injury. In fact, poor post-operative outcomes from surgical treatments in this area may be attributable to a lack of anatomical understanding. Studies demonstrate the intimate relationships between structures often targeted for surgical release and those which must be maintained. These relations, and particularly the innovative three-dimensional visualisations developed from these data, may inform significant advances in first ray health care.

Declaration

This thesis comprises only my original work towards the Doctor of Philosophy, except where indicated in the preface. Due acknowledgement has been made in the text to all other material used. The thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.



Casper Thorpe Lowis
November 2021

Preface

The work presented in this thesis is my own, yet many of the preparatory processes required collaboration. Preparation of Body Donors, prior to dissection, scanning or imaging, was done by the Anatomical Services Team in the Department of Anatomy and Physiology, The University of Melbourne. Computed Topographic (CT) imaging was undertaken at the Melbourne Brain Imaging Centre and done by Mr Robert Williams. MicroCT imaging was undertaken at the Melbourne Dental Hospital and done by Dr Rita Hardiman. Histologic processing was undertaken at the Melbourne Histology Platform with the assistance of Laura Leone. For all these processes, the experimental design, digital processing and data analysis was my own.

My supervisors, Associate Professor Quentin Fogg and Mr William Edwards, contributed to the editing and academic content of this thesis, yet the interpretations, analyses and conclusions are my own. This work has not been submitted for any other qualification and this thesis was carried out during the enrolment period of this degree.

The works presented in this thesis have not been submitted for publication but were constructed with the intention of submitting each chapter for publication. Restrictions to COVID-19 have delayed access to key resources in each area, preventing prior submission of these works.

Data from these studies have been presented nationally and internationally, as follows:

American Association of Clinical Anatomists (2020) *The clinical anatomy of the hallucal sesamoids*. AACCA Online.

Australian and New Zealand Association of Clinical Anatomists (2019) *3D micro-CT to demonstrate the detailed spatial arrangement of the nutrient foramina of the hallucal sesamoids*. Perth, Australia.

Australian and New Zealand Association of Clinical Anatomists (2019) *Attachments to the hallucal sesamoids: a sectional anatomy and sheet plastination study*. Perth, Australia.

European Association of Clinical Anatomy (2019) *The attachments of the deep transverse metatarsal ligament onto the lateral sesamoid*. Madrid, Spain.

European Association of Clinical Anatomy (2019) *The attachments of the adductor hallucis heads onto the lateral sesamoid*. Madrid, Spain.

AWARDED BEST POSTER

Australian and New Zealand Association of Clinical Anatomists (2018) *Attachments to the medial aspect of the medial hallucal sesamoid bone*. Townsville, Australia. **AWARDED BEST POSTER**

Restrictions due to COVID-19 limited these studies. Closure of the Body Donor Program, Histology Platform, and imaging centres through large parts of 2020 and 2021 resulted in rearrangement of the project plan to place greater emphasis on dissecting the available resources, with less emphasis

on imaging than initially planned. Those areas of the thesis that were well-resourced throughout the enrolment period are presented in Part 2, whilst Part 3 primarily includes those undertaken with limited resources and access due to the extended COVID-19 lockdown in Melbourne.

The results of these studies were also intended for presentation at surgical conferences in 2020 and 2021. These opportunities were either cancelled or delayed until 2022. The restrictions enforced in 2020 and 2021 also limited opportunities to engage in a clinical setting, which is important for more complete contextualisation and application of the data presented.

This PhD program was supported by an Australian Government Research Training Program Scholarship, after initial support from the Department of Anatomy and Neuroscience in the form of Fee Offset and Student Stipend Scholarships.

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I would like to acknowledge those who helped me achieve this behemoth task which was this collection of works.

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-Melbourne Histology platform particularly Laura Leone

-Melbourne Brain Center Imaging Unit, particularly Rob Williams

-My colleague and friend to share the torment with Georga Bruechert

-My family, for not disowning me for being a perpetual student.

-My beautiful partner Dr Rosalind Cook, who is the most breathtaking support of my ambitions and dreams. Without whom I would have never tried to match her title.

The Body Donors and their families, without whom none of this work would be possible, thank you.

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Part 1

Context, Current Understanding and Prevalence

Part One, Chapter One

1.1 The Legend of the Hallucal Sesamoids

The sesamoid, a small and unyielding bone, is incorruptible and indestructible by either fire, water or force, which does not decay when buried (Singer et al., 1904).

A bone that houses the soul, that when planted can grow a living man as from a seed (Münster, 1489-1552).

Where on the day of last judgement when watered with heavenly dew the dead will rise as with yeast in a mass of dough, and God shall lay upon them sinews, bring flesh, cover with skin and put in breath, to ultimately bring life.(Münster, 1489-1552); Figure 1.1.1).

The hallucal sesamoids have been intertwined with mysticism, with the first descriptions being made by theologians and philosophers, rather than anatomists or clinicians. The hallucal sesamoids are a paired set of bones found bilaterally at the plantar surface of the first metatarsal head (Kelikian et al., 2011). Once steeped in mystery and symbolism, their mythology and link to theology starts with the concept of an indestructible bone somewhere in the body that could house the soul (Singer et al., 1904).

Ancient Hebrew texts, such as the Genesis Rabba (B'reshith Rabba), mention a bone called the *luz* that is indestructible from which God will cause man to grow on a day of resurrection (Neusner et al., 1985). The fable continues that it cannot be rubbed out, cannot be burned, nor dissolved in

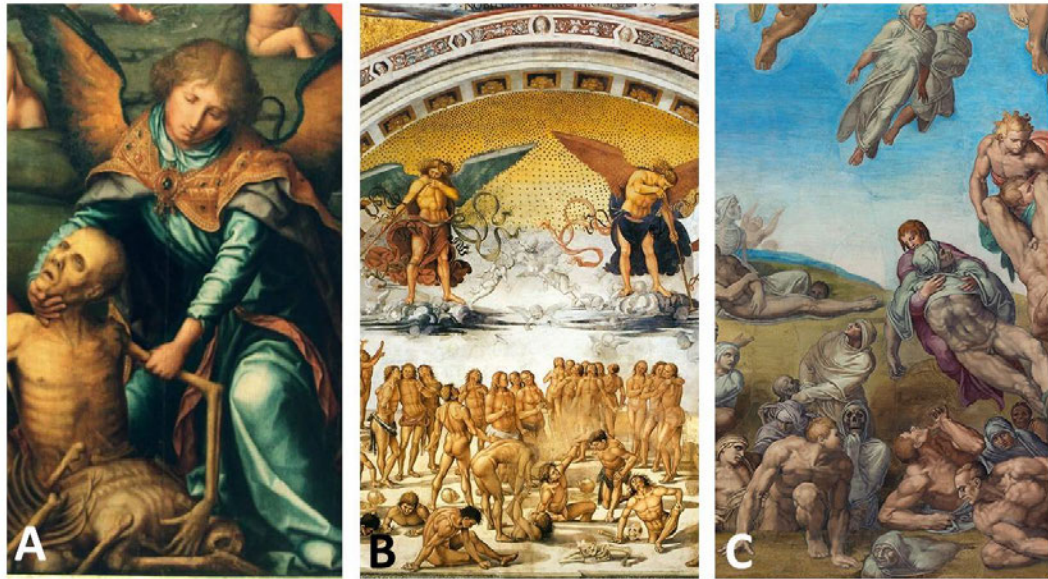


Figure 1.1.1. Three representations of resurrection on Judgement Day. A- An angel helping the resurrection of a chosen one, a close-up of the base of the central triptych of Last Judgement by Jehan Bellegambe the Elder (1520-1525), public domain image sourced from: commons.wikimedia.org/wiki/File:1523_Bellegambe_The_Last_Judgement_anagoria.jpg. B- A scene of resurrection on the day of the apocalypse,” scene of the damned and elect “being risen by angels, a fresco by Luca Signorelli (1499-1502). Public domain image sourced from: www.travelingintuscany.com/art/lucasignorelli/sanbriziochapel.htm, C - The resurrection in the flesh, “the supreme act of divine mercy” from the lowermost section of the Sistine fresco by Michelangelo (1508-1512). Public domain image sourced from: [https://commons.wikimedia.org/wiki/File:Last_Judgement_\(Michelangelo\).jpg](https://commons.wikimedia.org/wiki/File:Last_Judgement_(Michelangelo).jpg)

water, and if it were to be subjected to a forge and struck with a hammer, that the anvil would split into pieces and the hammer would break before anything was lacking to the bone (Neusner *et al.*, 1985).

The term *luz* in Hebrew means nut, almond or hazel, and was also the name of an ancient city said to have resisted Nebuchadnezzar and Hadrian, suggesting it to be impregnable and indestructible (Landman *et al.*, 1943). The meaning for the *luz* of interest here, is of that indestructible bone from Rabbinic law, and its mystical powers. However, the term used for these bones in Terminologia Anatomica and this work, is “sesamoid”. The term sesamoid is thought to have originated from Galen (129-210 CE) for the bone’s resemblance to *sesamum indicum* (sesame seeds), as opposed to the nut or almond in Hebrew, these sesame seeds were used as a purgative agent in ancient Greece and so had a medicinal connotation (Inge *et al.*, 1933).

To which bone the legendary *luz* actually refers is debated. In the secret laws, i.e., the mystical or kabbalistic literature of the Hebrews, the bone is said to be in the *neibe* which can be interpreted as the neck. This bone is described as very hard, cannot be burnt and will not putrefy when buried (Münster, 1489-1552). Another location of the bone was to be at the base of the vertebral column as mentioned in the Midrash Rabba (Freedman, 1961), and in B’reshith Rabba or *Glossa magna in Pentateuchum* (210 CE) written by the Rabbi Ushaia who explored ancient grave sites to find the best preserved bones to identify these soul housings. He suggested the *luz* to

belong to the *shedrah* (backbone) , and to sit below the 18th *chulia* (vertebra) and so would be the coccyx, as it is roughly almond shaped (Beddoes *et al.*, 2020). The proposed position in the neck or coccyx was moved inferiorly to the foot by unknown sources filtering through Arabic and Hebraic sources during the middle ages and later examined by anatomists, notably Vesalius (Garrison, 1910; Vesalius, 1543). This change in position is most likely because of the lack of any clear almond shaped bone in the neck or the spine (Garrison, 1910). Whereas the hallucal sesamoids are almond shaped and because of their compact and robust nature (Pretterklieber, 1990), they are smooth in appearance with minimal riddling from associated vessels (Pretterklieber *et al.*, 1992) and so would resist decay better than many other buried bones (Vesalius, 1543).

In the year 1539CE, in the Christian -Jewish polemic book *Sefer Ha- Veekuakh* (Basel, 1539) by Sebastian Münster, the subject of this bone is once again broached (Münster, 1489-1552), and again in an anatomical context in *De humani corporis fabrica libri septem* (Vesalius, 1543).

The works of Vesalius ascribe the title of *Albadaran* to the sesamoid bones of the great toe, claiming the same mythology as the *luz* but through an Arabic incarnation (Garrison, 1910). This term, *Aldabaran*, is in reference to *aldadra*, small gold coins of equal size as the hallucal sesamoids, given to the assembly by the mother of the bride at a wedding. The *Aldabaran* is thus the sower of these coins or “seeds”, the term can also be translated as “Two

new moons” (Helal, 1981), perhaps in reference to the two hallucal sesamoids and the fecundity of a new moon.

The question of which of the four hallucal sesamoids supposedly houses the soul is elucidated by Vesalius, suggesting the bone in question to be “the internal ossicle of the right great toe” that contains the occult powers (Vesalius, 1543). This location may have been inspired by the biography of King Pyrrhus in *Parallel Lives* by Plutarch, which states that the right great toe of King Pyrrhus had divine virtue and could heal the spleen. After his death he was cremated, with only his right great toe found unhurt and untouched by the fire (Plutarchos *et al.*, 1920). This fits with a mysticism and incombustibility that are associated with the *luz*.

Vesalius did, however, discount the “immense fiction” of the *luz* being the sesamoids, after disproving their powers by noting they can be burnt and broken, highlighting they are durable but still liable to decay.

Girolamo Maggi (Maggi, 1572) reinstated the views of Vesalius, in that the sesamoids are indeed the *luz*, and brings forward once again the Hebraic story of the incorruptible bone found either in the neck or the 12th vertebra (Singer *et al.*, 1904).

Caspar Bauhinus reviewed the stories of the *lus* in the anatomical text *Theatricum Anatomicum* (Bauhin, 1605)), discounting the myth of a bone of resurrection.

The poet and physician, Thomas Lovell Beddoes, took an interest in ancient Hebrew legends and is said to have even carried out his own dissections in search of the *luz*, with no apparent success. He does, however, introduce the *luz* in a scene of resurrection in Death's Jest-Book (Beddoes *et al.*, 2020; Moylan, 2008).

*The herb was born anew out of a seed,
Not raised out of a bony skeleton.*

What tree is man the seed of?

*And even as there is a round dry grain
In a plant's skeleton, which being buried
Can raise the herb's green body up again;
So is there such in man, a seed-shaped bone,
Aldabaron, called by the Hebrews Luz,
Which, being laid into the ground, will bear
After three thousand years the grass of flesh,
The bloody, soul-possessed weed called man.*

(Beddoes *et al.*, 2020)

The direct association of bones with seeds is made with a cherry stone being a bone, and the stem being a foot or leg. This association is found in the third book of Nostradamus, which is not concerned with prophecies but rather "A treatise in makeup and cooking" (Traité des

fardemens et confitures;(Nostradamus, 1555). Written in old French in 1555, a suggestion that the stones of fruit may have been referred to as bones at the end of feet or legs is included, once again conjuring up the idea of sprouting a person, much like the growing of a plant.

There is a similar phenomenon to the indestructible *luz* in Buddhism. In Sanskrit they are termed *Śarīra*, which translates as “Body” or “Relic”, these relics are small ovoid shaped, pearl like items said to be indestructible (Figure 1.1.2). These *Śarīra* are found in the ashes of cremated monks and Buddhist masters and are said to be crystalline representations of the holiness of the cremated. Their beauty is suggested to correlate to the level of enlightenment of the individual (Strong, 2018; Suzuki, 1940). Forensic study has found that bones can indeed crystallise at high temperatures, perhaps giving credence to the presence of these unusual relics in the ashes of the mighty pyres of holy men (Holden *et al.*, 1995).



Figure 1.1.2. Buddhist Sarira, have a hallucal sesamoid-like shape and are thought to represent and embody the spirituality of an individual of great spiritual enlightenment. These Sarira are from His Holiness Supreme Patriarch of Thailand in Wat Khung Taphao Buddhist temple. Public domain image sourced from <https://www.atlasobscura.com/articles/buddhist-human-pearls>.

In Japan, there is still a custom where the ashes of the cremated are sifted through to identify bony structures, which are then placed in an urn and left at a temple for forty nine days before being buried (Strong, 2018). These religious parallels from the east are another facet of the belief of immortality through physical manifestations such as bones or similar artefacts or relics, which often resemble the size and shape of hallucal sesamoids.

To summarise the story of the *luz* or hallucal sesamoids; they are famed as bones incorruptible and indestructible by either fire, water, or force, and that do not decay when buried. They have been hailed as housing the soul, that when planted can grow a living person as from a seed (Butler, 1772; Vesalius, 1543). Where on the day of last judgement when watered with heavenly dew the dead will rise as with yeast in a mass of dough (B'reshith Rabbi, Theatricum anatomicum), and God shall lay sinews, bring flesh, cover with skin and put in breath, to ultimately bring life (Münster, 1489-1552). This tale perpetuated throughout history by theologians, followers of the occult, poets and dramatists, and importantly in this context, anatomists, is a colourful and interesting journey to find a bone, and is to this day, still repeated in contemporary literature (Boike *et al.*, 2011; Dedmond *et al.*, 2006; Gerber *et al.*, 2000; Helal *et al.*, 1986; Inge *et al.*, 1933; Jamal *et al.*, 2015; Julsrud, 1997; Potter *et al.*, 1992; Richardson, 1987; Van Hal *et al.*, 1982).

Doubtless the *luz*, or sesamoids, with their illustrious history and mysticism, have inspired many stories and poems (Beddoes *et al.*, 2020;

Butler, 1772; Moylan, 2008) and much art (Figure 1.1.1) that have shaped culture. The story is interesting and a culturally important feature of the hallucal sesamoid bones.

The presented chronological history of the sesamoids and their legend is a historical perspective and in a few ways is based off the anatomy of the structures themselves. This review demonstrated the value of a clearer appreciation of history, truth-seeking and deeply held meaning often associated with our bodies. In a modern setting, anatomists continue the respectful investigation of our bodies, helping us to better treat illness and injury, and to also understand who we are on a deeper level.

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Part One, Chapter Two

1.2 The Hallucal Sesamoids: A review of the literature

1.2.1 Hallucal Sesamoid Introduction

The hallucal sesamoids (HS) are important features of the great toe apparatus and are often implicated in dysfunction of the first ray of the foot. They are rarely the primary focus of much of the literature, they are most often encompassed within the description of other structures, such as the flexor hallucis brevis (FHB) heads (Coughlin, 1996; Ger, 1988; Waldrop III *et al.*, 2013) (Figure 1.2.1), or within the biomechanical unit of the first metatarsophalangeal joint (MTPJ) (Figure 1.2.1). The HS are also part of a number of pathologies which substantiate their clinical relevance and functional importance within the foot. The most common of these pathologies and their aetiologies will be reviewed with specific focus on the role that the HS play within their attributed pathomechanisms. The most commonly cited pathology relating to the HS is hallux valgus, followed by turf toe, sesamoiditis, acute trauma and fractures as well as hallux varus and avascular necrosis (Beaman *et al.*, 1999).

This review will establish the baseline level of information for the HS. The HS are part of the first metatarsophalangeal joint (MTPJ) complex. The two HS lie inferior to the head of the first metatarsal (MT) bone. The medial sesamoid (MS) and lateral sesamoid (LS) are often termed the tibial sesamoid and the fibular (peroneal) sesamoid, respectively.

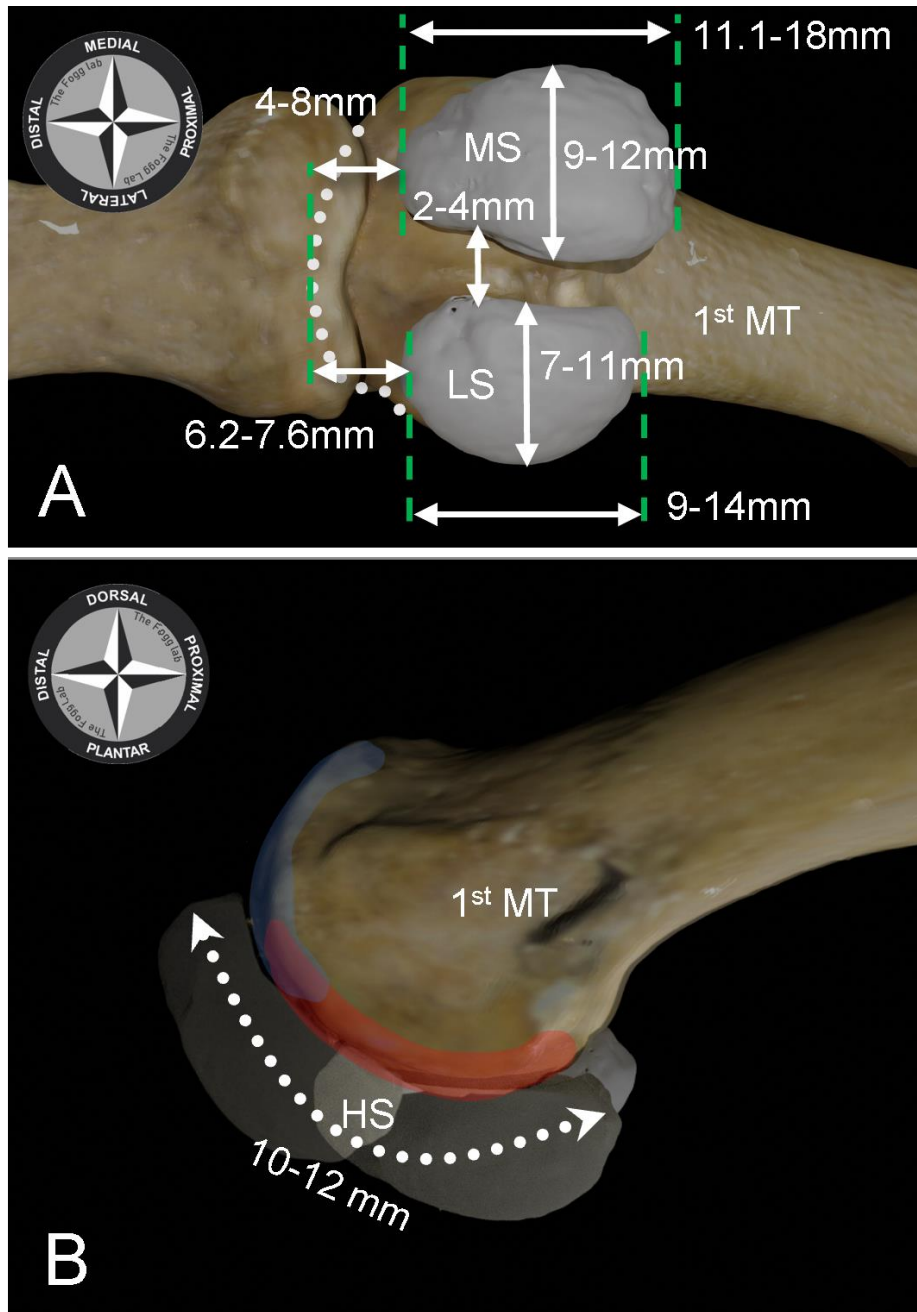


Figure 1.2.1. Models of the sesamoid interactions: A - The first metatarsal (1st MT) and proximal phalanx with lateral (LS) and medial (MS) sesamoids with their average dimensions and distance from the MTPJ line, demonstrating the greater length, breadth and distal positioning of the hallux sesamoids (HS). B - A Lateral view of the first metatarsal head with articular surfaces for the proximal phalanx and hallux sesamoids respectively, plantar to which a lateral sesamoid ghost along its tracking distance (white dotted arrow).

1.2.2 Hallucal Sesamoid Overview

The resemblance of the HS have been compared to that of coffee beans (Haines *et al.*, 1954; Kewenter, 1936), in that they are convex on their non-articular plantar surface and are roughly of similar size. The similarity ends at their dorsal slightly concave articular surface, to be congruent to the corresponding articular surface contour of the first MT head (Haines *et al.*, 1954; Kelikian *et al.*, 2011; Richardson, 1987) (Figure 1.2.1).

The HS are a constant feature within the foot, unlike up to 13 or more other inconstant accessory ossicles and sesamoids reported within the foot alone (Anwar *et al.*, 2005; Bizarro, 1921; Coskun *et al.*, 2009; Inge *et al.*, 1933; Kelikian *et al.*, 2011; Koo *et al.*, 2017; Nwawka *et al.*, 2013; Pfitzner, 1892; Trolle, 1948; Yammine, 2015). The HS are relatively large in comparison to the inconstant sesamoids; they are the largest sesamoid bones in the body after the patella (Bizarro, 1921; Cunningham *et al.*, 2017; Orr, 1918; Pfitzner, 1892). The fact that the paired HS are a constant, suggests an important role.

The very first sign of the HS is their appearance as islands of undifferentiated connective tissue beneath the MT head within the joint capsule at eight weeks *in utero*, (Inge *et al.*, 1933; Kelikian *et al.*, 2011). At 11 to 12 weeks *in utero*, the chondrified anlagen of the sesamoids are easily identifiable with all of their surrounding components (Brenner *et al.*, 2002; Gardner *et al.*, 1959; Takahashi, 1954). The LS appears one week prior to

the MS (Takahashi, 1954). By the fifth month of development the sesamoids are said to have their adult shape and from then on, their development is said to only be in size (Inge *et al.*, 1933; Kewenter, 1936), until they ossify, starting at around the age of eight years and finishing by the age of eleven (Dharap *et al.*, 2007; Inge *et al.*, 1933). Even within this early stage of observation of the HS, there are suggested differences in ossification times between the sexes, where female HS ossify before those of the male (Allen, 1926; Dharap *et al.*, 2007; Hasselwander, 1924; Kewenter, 1936; Ruckensteiner, 1931). Kewenter (1936) determined that female HS ossify about two years before those of males (Kewenter, 1936). It has also been suggested that the ossification of the LS precedes that of the MS (Kelikian *et al.*, 2011; Potter *et al.*, 1992).

The MS is described as being slightly longer than the LS, giving it an ovoid appearance, with a sagittal length of 11.1-18mm and a coronal width of 8-12mm (Gillette, 1872; Lucas *et al.*, 2014; McBryde *et al.*, 1988; Munuera *et al.*, 2008; Pretterklieber, 1990; Richardson, 1987; Theumann *et al.*, 2002). The LS is thus shorter with a more circular appearance and a length of 9-14mm and a width of 7-11mm. These data were gathered from most likely European (or European-descended) populations so may not reflect other populations, and some of the data was not adjusted for individual size (Gillette, 1872; Kewenter, 1936; McBryde *et al.*, 1988; Pretterklieber, 1990; Richardson, 1987; Theumann *et al.*, 2002). A study on a Chinese Han population identified a different pattern where the LS were larger than the MS in 65.3% of their sample, with the LS being 11.8mm long and 8.94mm wide

on average and the MS being 11.75mm long and 8.19mm wide on average (Zhang *et al.*, 2020). However, in general, the MS is said to be broader than the LS (Kewenter, 1936), and that the MS is larger than the LS, It is also stated that they are of equal size about a third of the time, and that the LS is rarely larger than the MS (Gillette, 1872; Karadaglis *et al.*, 2003; Kewenter, 1936; McBryde *et al.*, 1988; Pretterklieber, 1990; Theumann *et al.*, 2002).

The distal tip of the MS is often the most distal of the two HS, and only rarely level with the LS. (Prieskorn *et al.*, 1993) (Figure 1.2.1).

Radiographically, the MS is on average 4.9mm proximal to the distal most point of the MT articular cartilage, whereas the LS is on average 6.2 - 7.6mm proximal to that same point (Lucas *et al.*, 2014; Munuera *et al.*, 2008; Prieskorn *et al.*, 1993) (Figure 1.2.1). Recognition of their normally asymmetric position is important for the diagnosis of turf toe, hallux limitus and hallux valgus, and potentially for the early identification of those predisposed to these conditions (Dayton *et al.*, 2014; Dayton *et al.*, 2013; McBryde *et al.*, 1988; McCormick *et al.*, 2010; Munuera *et al.*, 2008). These conditions act on deforming the sesamoids and their surrounding tissues, suggesting that differences in position from the norm in plain X-rays can be diagnostic (Hummel *et al.*, 2019).

The HS are similar in size, but distinct in appearance, driven by their differing soft tissue relations. Tendino-ligamentous units interact with the HS before they are fully formed, influencing their shape and the extent and orientation of the interactions they will have with the first MT head, muscles and fibrous tissues (Pretterklieber, 1990). The precise nature of these interactions is not clearly understood. Some studies suggest the MS to receive attachments from the abductor hallucis tendon and the medial head tendon of the FHB muscle (Coughlin *et al.*, 2013; Pretterklieber, 1990). These muscles would exert forces in a longitudinal direction onto the sesamoid bone precursor, creating the elliptical shape of the MS (Pretterklieber, 1990). The LS is reported to receive attachments from the tendons of the two heads of the adductor hallucis muscle (Shereff, 1990), the lateral head tendon of the FHB muscle, and the first deep transverse metatarsal ligament (DTMTL) (Barg *et al.*, 2012; Coughlin *et al.*, 2013; Kelikian *et al.*, 2011; Pretterklieber, 1990). The pull from these structures is suggested to be more transverse, thus the more circular shape of the LS (Carter, 1987; Pretterklieber, 1990; Preuschoft, 1969). To help confirm the directional deformation by the associated muscles, histological and biomechanical testing studies would be beneficial to verify these stresses onto the nascent HS. A breakdown of the differences between the medial and lateral HS is shown in Table 1.2.1.

Table 1.2.1. Areas of difference between hallucal sesamoids, reported in the reviewed literature. The literature suggests that the medial and lateral sesamoids are distinctly different and that a common impression of each has been maintained.

Areas of Difference:	Lateral Sesamoid	Medial Sesamoid
Appearance in Utero (Inge <i>et al.</i> , 1933; Kelikian <i>et al.</i> , 2011)	56 days in utero	56 days in utero
Chondrification (Takahashi, 1954)	75 days in utero	82 days in utero
Ossification (Allen, 1926; Dharap <i>et al.</i> , 2007; Hasselwander, 1924; Kewenter, 1936; Ruckenstein, 1931) (Kelikian <i>et al.</i> , 2011; Potter <i>et al.</i> , 1992)	8-11 years old, preceding MS	8-11 years old
Size and Morphology (Gillette, 1872; Lucas <i>et al.</i> , 2014; McBryde <i>et al.</i> , 1988; Munuera <i>et al.</i> , 2008; Pretterklieber, 1990; Richardson, 1987; Theumann <i>et al.</i> , 2002) (Karadaglis and Grace 2003) (Prieskorn <i>et al.</i> , 1993)	9-14mm long, 7-11 wide, smaller, and more circular in appearance	11.1-18mm long, 8-12mm wide, larger, and more ovoid in appearance
Robusticity (Pretterklieber, 1990) (Susman <i>et al.</i> , 1988) (Stauber <i>et al.</i> , 2014; Stock <i>et al.</i> , 2007)	More Robust	Less Robust
Rate of Injury (Beaman <i>et al.</i> , 1999; Cunningham <i>et al.</i> , 2017; Dedmond <i>et al.</i> , 2006; Freiberg, 1920; Inge <i>et al.</i> , 1933; Julsrud, 1997; Kadakia <i>et al.</i> , 2011; McCormick <i>et al.</i> , 2009; Sims <i>et al.</i> , 2014)	Fewer mentions within the clinical literature for most types of hallucal sesamoid injury.	Most likely damaged as it sits directly in line with weight transfer and is larger.
Current suggestions of Attachment (Barg <i>et al.</i> , 2012; Coughlin <i>et al.</i> , 2013; Kelikian <i>et al.</i> , 2011; Pretterklieber, 1990) (Shereff, 1990)	Adductor Hallucis, FHB Lateral head, PP, DTMTL, PA, Lateral	Abductor Hallucis, FHB medial head, PP, Lat
Rate of Partism (Yammine, 2015)	1.3% of the population	10.7% of the population
Rate of Absence (Karadaglis <i>et al.</i> , 2003)	0.08% of the population	0.25% of the population

1.2.3 Hallucal Sesamoid Interactions

Metatarsal Head

The first interaction that the HS are most obviously associated with is the first MT head, as they are said to emerge from the first MTPJ capsule itself (Inge *et al.*, 1933). Considering a foot in the neutral position, where the first MTPJ is in 16-20 degrees of extension (Yoshioka *et al.*, 1988), the medial and lateral HS both sit on the plantar surface of the large, rounded, cartilage-covered MT head (Figure 1.2.1B). This structure is the primary articulating interaction for the HS (Cunningham *et al.*, 2017; Haines *et al.*, 1954; Kelikian *et al.*, 2011; Nery *et al.*, 2017). The convex, dorsal third of the MT head is the part that articulates with the proximal phalanx. The inferior/plantar two thirds of the MT head have two parallel longitudinal grooves, sometimes known as trochlear surfaces. These are the medial and lateral grooves for the medial and lateral HS respectively. The medial groove was longer (16.73mm), deeper and narrower (10.81mm), compared to the lateral groove (15.35mm long and 11.6mm wide; (Cunningham *et al.*, 2017; Pretterklieber, 1990). This corresponds with the average differences in size found between the two HS (Kewenter, 1936). Each groove contained a small longitudinal indent in the midline that fit a midline crest on the HS articular surfaces (Kelikian *et al.*, 2011). Within the grooves, the HS are said to track 10-12mm during normal dorsiflexion of the first MTPJ (Shereff, 1990). The grooves are separated by a smooth ridge called the intersesamoid crista (Cunningham *et al.*, 2017; Doty *et al.*, 2013; Kelikian *et al.*, 2011; Muehleman

et al., 1997; Stainsby, 1997). The intersesamoid crista was bony, covered in articular cartilage and varied in size between individuals (Maddocks *et al.*, 2017; Yoshioka *et al.*, 1988). It is not clear what percentage of the functional intersesamoid crista is made up of cartilage versus bone, and how each component is affected in conditions such as HV, where it is eroded away during the lateral subluxation of the HS. Further research is required to determine the exact makeup of the intersesamoid crista, which would clarify how accurate X-ray diagnostic imaging is in determining the mechanisms and severity of conditions such as HV (Hummel *et al.*, 2019; Maddocks *et al.*, 2017).

Despite the separation of sesamoids by the intersesamoid crista, and their individual attachments, both are linked to each other and the MT head (Anwar *et al.*, 2005). This close relationship to each other, the MT head and the proximal phalanx is maintained with several tendinous and ligamentous connecting structures (Alvarez *et al.*, 1984).

Hallucal Plantar Plate

There is no consensus on soft tissue interactions with the first MTPJ. The most notable soft tissue relation of the HS is the plantar plate (PP). The Plantar plate (PP) is often referred to in the literature; it is mentioned in the context of the hallux 80 times in Pubmed and in Web of Science 182 times (as of 12/07/2021). Despite this there is no consensus as to what forms it. The term is used as a stand-in for any description of the fibrous structures at

the plantar aspect of the first MTPJ. As with most anatomical terminology, there are different terms for the same structure, this leads to an inability to identify the relevant literature. The Other terms for the plantar plate include glenoid ligament of Cruveilhier (Valvo *et al.*, 1987), glenosesamoid pad (de Britto, 1982; Potter *et al.*, 1992), plantar pad (Alvarez *et al.*, 1984; Aseyo *et al.*, 1984; Hicks, 1954) or plantar ligament (Gu *et al.*, 2012) or volar accessory ligament (Sanders *et al.*, 2008) as well as volar plate (Jahss, 1980; Trikha *et al.*, 2009; Wong, 2007), although plantar plate is the most commonly used and will be the main term used here.

Considering the variance in terminology, there are few papers that make description of it, but when mentioned it is most often found represented in illustrations, these are as varied and ambiguous as written descriptions. (Figure 1.2.2) Some have defined the PP as a single structure, such as the intersesamoid ligament (Netter, 2014), or even as each sesamophalangeal ligament (Linklater, 2012). Another proposed single PP entity is the fibrous tissue between the two sesamophalangeal ligaments (Crain *et al.*, 2008; Stoller, 2007). The more common description of the PP is that it is more than a single ligament, for example it has been defined as a pair of structures such as both sesamophalangeal ligaments together (Crain *et al.*, 2016). There are some that propose the PP to not be a separate ligament or pair of ligaments but to be the extension of the flexor hallucis brevis tendons attaching to the HS and the base of the proximal phalanx (Coughlin, 1996; Sims *et al.*, 2014) (Figure 1.2.2B).

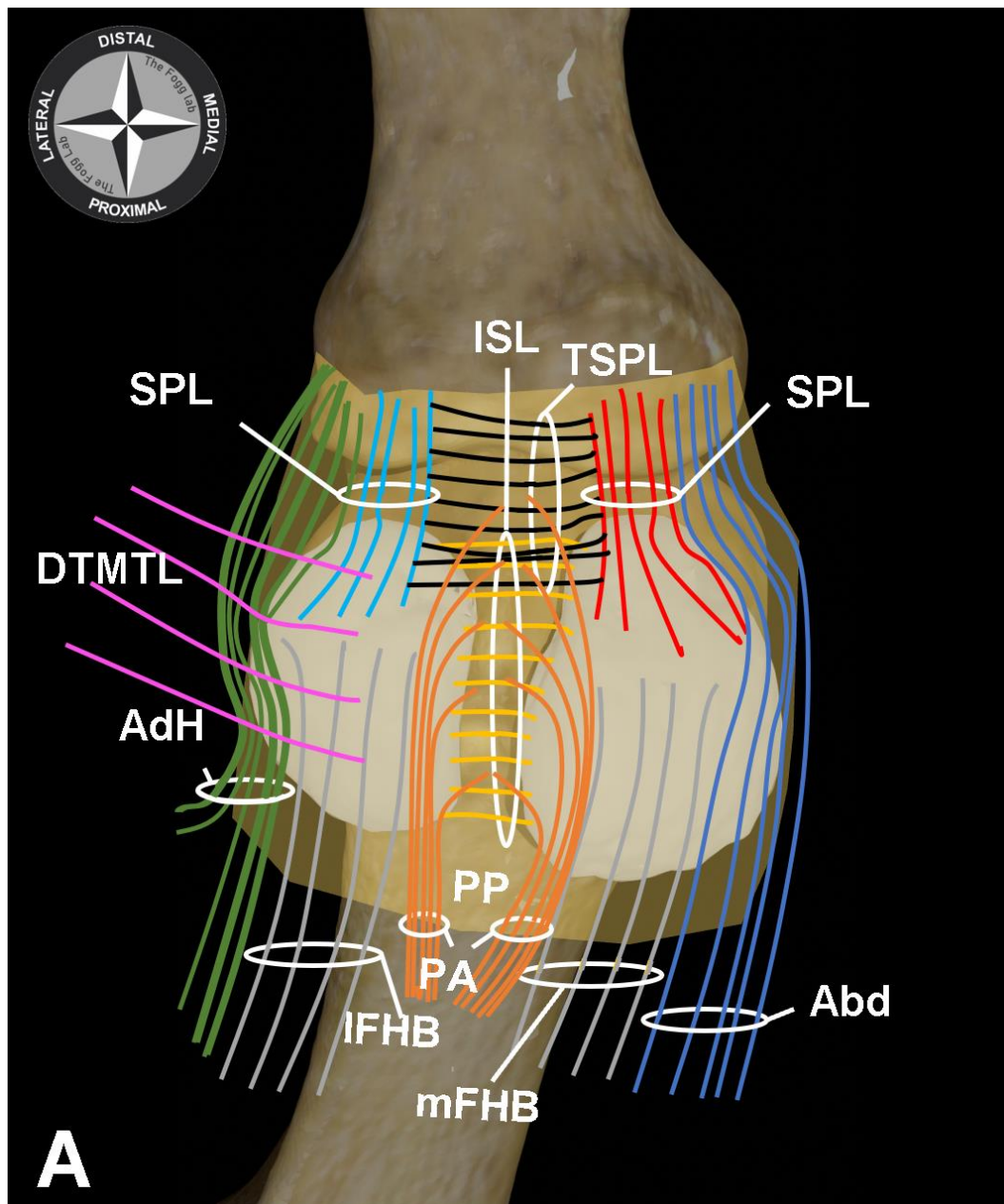


Figure 1.2.2. Current descriptions of the plantar plate. A - The conglomeration of many elements making up the plantar plate (PP, transparent yellow oblong), with incoming tendons such as the Adductor Hallucis heads (AdH, green lines), the abductor hallucis (Abd, blue lines), the two flexor hallucis brevis (IFHB and MFHB, grey lines). Connecting to the more embedded ligaments such as the Intersesamoid ligament (ISL, yellow lines), and the sesamophalangeal ligaments (SPL, cyan and red lines) and the transverse sesamophalangeal ligament (TSPL, black lines). With further additions such as the plantar aponeurosis (PA, orange lines) and the deep transverse metatarsal ligament (DTMTL, pink lines). (All shown attachment points are arbitrary, as the literature does not specify). *Figure continues on the next page.*

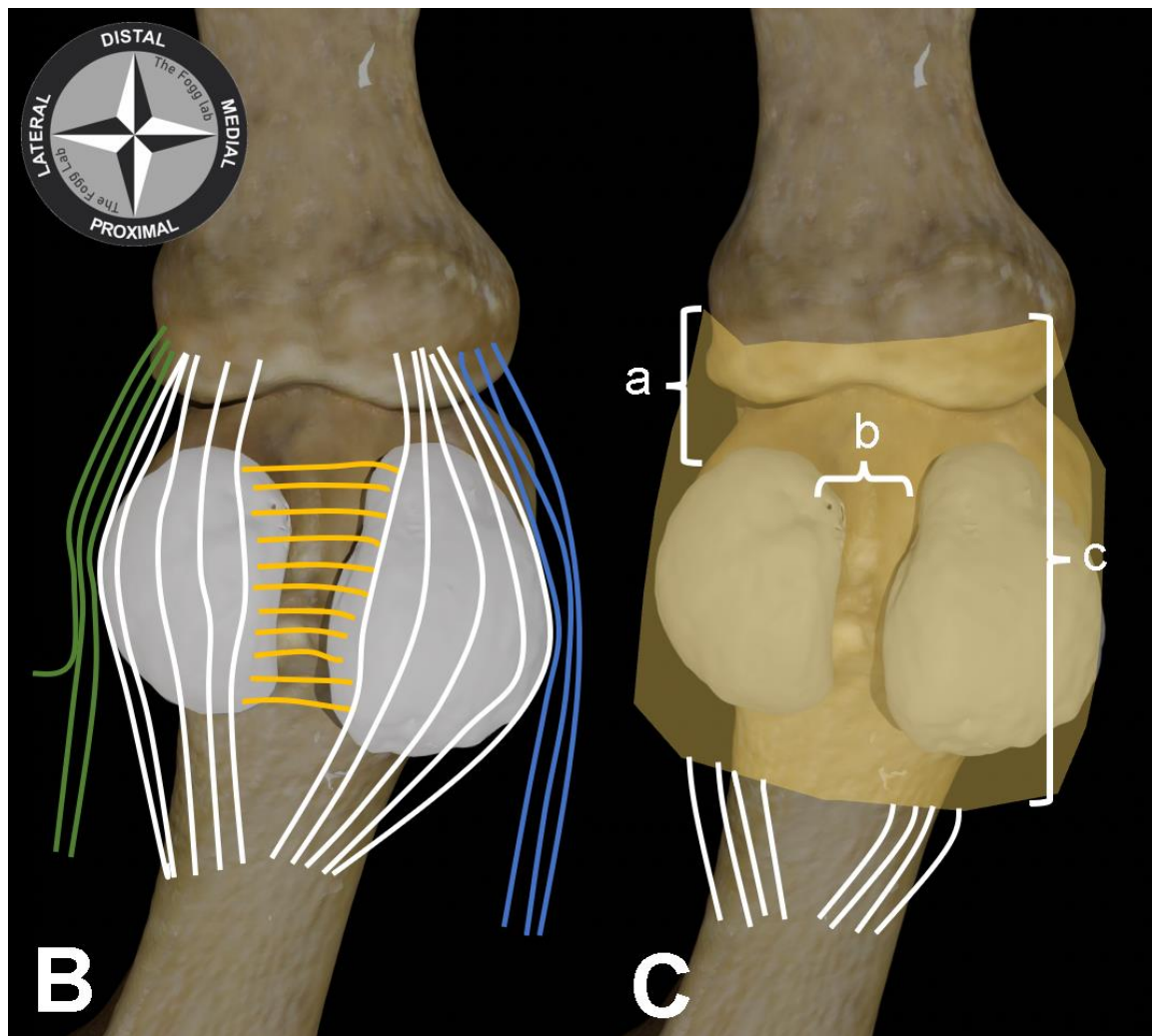


Figure 1.2.2. *continued*. B- A more common description of the plantar plate where both hallual sesamoids are fully enveloped in their respective flexor hallucis brevis tendons (white lines), and are connected by the Intersesamoid ligament, with no connection between the sesamoids and the incoming tendons. C- The same plantar view with an often referred to plantar plate, a single entity of fibrocartilage filling the plantar aspect of the metatarsophalangeal joint and embedding both hallual sesamoids. The fibrocartilage being connected to by some incoming tendons and ligaments, most likely the flexor hallucis brevis tendons. The current literature views certain areas as being the PP, such as just the distal part between the HS and the proximal phalanx (a). Some authors believe it to be just the central component between the HS (b), whereas some describe the PP as encompassing the whole MT neck to proximal phalanx area (c).

Others have defined it by area (Figure 1.2.2C), such as any fibrous tissue or fibrocartilaginous structure connecting the hallucal sesamoids to the proximal phalanx (Anderson *et al.*, 2007; Joseph *et al.*, 2007; McCormick *et al.*, 2009; Richardson, 1999), or indeed most classically spanning from the first MT neck to the base of the proximal phalanx (Anwar *et al.*, 2005; Gregg *et al.*, 2007b; Hicks, 1954; Kanatli *et al.*, 2006; Lucas *et al.*, 2014; Nery *et al.*, 2017; Stoller, 2007; Theumann *et al.*, 2002) or simply encompassing the sesamoids and being connected to by incoming hallucal tendons and ligaments (Alvarez *et al.*, 1984; Anwar *et al.*, 2005; Aseyo *et al.*, 1984; Potter *et al.*, 1992; York *et al.*, 2017).

There are those who have defined the PP as a complex (Figure 1.2.2A), not a fibrocartilaginous structure but a confluence of tendons and ligaments that are on the plantar aspect of the hallux (Beaman *et al.*, 1999; Coughlin *et al.*, 2013). This definition has many variables, some include the most plantar structures only, such as the flexor hallucis brevis tendons, the plantar aponeurosis, the abductor and adductor tendons, the sesamophalangeal ligaments as well as the intersesamoid ligaments, and all tissues between them, and a common description includes the intersesamoid as being a central portion of the PP (Boike *et al.*, 2011; Dedmond *et al.*, 2006; Richardson, 1987; Sanders *et al.*, 2008).

There are however some that include some more medial and lateral structure contributions such as the collateral ligaments (Barg *et al.*, 2012; Brenner *et al.*, 2002; Dedmond *et al.*, 2006), the deep transverse metatarsal

ligament (Brenner *et al.*, 2002; Nery *et al.*, 2017) and fibres from the extensor hood (Nery *et al.*, 2017), as well as the synovial capsule of the first MTPJ (Brenner *et al.*, 2002; Kanatli *et al.*, 2006).

The importance of the plantar aponeurosis in the makeup of the PP varies in the literature, it can be a contribution amongst many (Nery *et al.*, 2017) or the main and most important component of the PP (Chen *et al.*, 2014; Kanatli *et al.*, 2006; Southerland *et al.*, 2012; Stainsby, 1997).

Interestingly there are some authors who allude to including the hallucal sesamoids as part of the PP (Jahss, 1980), as they develop inside of the PP at 12 weeks *in utero* according to Richardson (Richardson, 1987).

It is critical that the first MTPJ plantar plate be anatomically described as it is referred to so often in the literature without definition, with an assumption that the reader knows what version of PP is meant (Abdalbary *et al.*, 2016; Fiacco *et al.*, 2017; Hummel *et al.*, 2019; Lucas *et al.*, 2014; Nihal *et al.*, 2009; Prieskorn *et al.*, 1993; Sammarco *et al.*, 2001; Sorene *et al.*, 2006; Valvo *et al.*, 1987). In studies proposing measures of the PP, the methodology is incomplete with the ambiguous definition of the structure, as there is no consensus (Hummel *et al.*, 2019).

The interaction that the sesamoids have with the PP is an important one, as they are said to be embedded within it (Haines *et al.*, 1954; Jamal *et al.*, 2015; Kelikian *et al.*, 2011; McCormick *et al.*, 2010; Richardson, 1987;

Richardson, 1999; Waldrop III *et al.*, 2013). This embedding of the sesamoids either into the PP or, as some describe, into the incoming tendons and ligaments, centred the sesamoids as foci of attachment (Kelikian *et al.*, 2011). The PP may hold the HS in position, this position is affected with conditions such as turf toe, where the PP is damaged and thus no longer stabilising the first MTPJ and sesamoid position, demonstrating the critical nature of the relationship between the PP and HS (Crain *et al.*, 2016; McCormick *et al.*, 2010). In turf toe, the HS were found more proximally as their more distal attachments to the proximal phalanx were severed, prompting unimpeded drag via their proximal attachments (Waldrop III *et al.*, 2013). More recently, a strong correlation between a torn PP and HV has been identified. The mechanism of action between the two pathologies has however, not been explored (Hummel *et al.*, 2019). Better understanding of the HS soft tissue attachments and their pattern of disruption is needed.

There are important biomechanical functions assigned the PPs, as they are intimately involved in the longitudinal and transverse “Tie-rods” of the foot. The first MTPJ PP is said to be the medial most attachment for the transverse tie-rod of the foot. It is made up of plantar plates and intervening deep transverse metatarsal ligaments which maintain the transverse arch of the forefoot and prevent excessive forefoot splaying (Stainsby, 1997; Wang *et al.*, 2015). The first MTPJ PP is also a distal attachment point for the plantar aponeurosis which is responsible for maintaining the medial and lateral longitudinal arches of the foot, as well as being critical components of the “windlass” mechanism (Bojsen-Moller *et al.*, 1976; Hicks, 1954). The PP

are crucial in the gliding movement of the first MTPJ (Boike *et al.*, 2011). These important biomechanical functions within the foot as a whole highlight the importance of understanding their anatomy.

As established the PP is not consistently described. The ambiguity of the makeup of the PP needs clarification, The PP is reportedly “difficult to visualise as a distinct structure unless thickened or surrounded by oedema” (Nery *et al.*, 2017). The anatomy of the PP of the first ray has not been a focus of much research, compared to the PPs of the lesser toes (Brenner, 1999; Deland *et al.*, 1995; Gregg *et al.*, 2006a; Gregg *et al.*, 2006b; Lucas *et al.*, 2014). Despite this, the literature can generally agree on a couple of aspects of first ray PP anatomy:

- That it has a stronger distal attachment to the proximal phalanx and a weaker proximal attachment to the MT head (Haines *et al.*, 1954; Kelikian *et al.*, 2011; McCormick *et al.*, 2010; Richardson, 1987).
- It contains and/or continues distal to the HS (Kelikian *et al.*, 2011; Nery *et al.*, 2017).

The research done on the PPs of the rays 2-5 help inform what could be expected in the first MTPJ PP, despite lacking the constant presence of sesamoid bones. Studies have found the PP of the first ray to be made up of fibrocartilaginous material, with a high type I collagen content and very little in terms of elastin, much like the lesser ray PPs (Deland *et al.*, 1995; Gregg *et al.*, 2006b). Histological volume density has been calculated for lesser toe PP

central fibres, highlighting that they are 64% regular dense connective tissue, 20% loose cellular tissue, 9% irregular connective tissue and 7% blood vessels (Gregg *et al.*, 2006b). Compositional data such as these could be furthered to identify distinct compositions of components feeding into the PP such as aforementioned tendons and ligaments. These additional data could confirm whether the first ray PP is a distinct structure. The longitudinal length of the PP (23.92mm without correcting for size) (Lucas *et al.*, 2014), was consistent with the measures of the second and third rays(18.8-20mm) (Deland *et al.*, 1995; Gregg *et al.*, 2007a; Gregg *et al.*, 2006b; Johnston *et al.*, 1994). The dorsal intra-articular surface of the PP was said to have an appearance of smooth articular cartilage (Deland *et al.*, 1995), thus the PP has been described as a thickened plantar aspect of the first MTPJ capsule (Inge *et al.*, 1933; Stainsby, 1997). Described as emerging from the dorsal surface of the PP are the articular surfaces of the medial and lateral HS, sitting in direct association with their contiguous medial and lateral grooves in the plantar surface of the first MT head. The HS are anchored to each other primarily due to their incorporation within the PP, and/or directly linked by the intersesamoid ligament (Cunningham *et al.*, 2017; Kelikian *et al.*, 2011; Richardson, 1987). This ligament may keep the HS at an average distance of 2-4 mm from each other (Kewenter, 1936; Prieskorn *et al.*, 1993) (Figure 1.2.1). The intersesamoid ligament was also found to form the dorsal surface of a fibrous tunnel for the passage of the flexor hallucis longus (FHL) tendon (Orr, 1918). Due to the position of the tunnel between the HS, it has been theorised that weight during ambulation is diverted onto the HS to protect the FHL tendon and its tunnel (Cunningham *et al.*, 2017), it isn't however clear

how the contiguous long flexor tunnel interacts with the PP but is likely to serve a supporting role.

The proximal ends of lesser toe PPs are thin (0.4mm) compared to the thickness of their more central parts (2.1-5mm) (Deland *et al.*, 1995; Gregg *et al.*, 2006b; Johnston *et al.*, 1994). The proximal portion of the PP was loosely attached to the plantar surface of the MT neck with a synovial-type tissue (Deland *et al.*, 1995; Gregg *et al.*, 2006b; Haines *et al.*, 1954; Kelikian *et al.*, 2011), but has been insufficient for MTPJ stability. The distal-most attachment of the PP has been described as a fibrocartilaginous rectangle, with its whole transverse length on the plantar aspect of the proximal phalanx (Haines *et al.*, 1954); Figure 1.2.2C). Some research has produced a slightly more detailed picture of the distal aspect, describing the PP as attaching in its entire thickness to the plantar surface of the proximal phalanx, making it a more robust connection (Deland *et al.*, 1995; Johnston *et al.*, 1994; Lucas *et al.*, 2014). Lucas *et al.* (2014) reported PP attachments in sagittal plane length, whereon the proximal phalanx the length of the PP attachment was greater (6.33mm) than proximally on the MT neck (0.4mm);(Lucas *et al.*, 2014). Whilst providing an excellent foundation for more detailed descriptions of the PP, the measurements were not reproducible, having no description of specific points of measurement. These data were also not indexed against the size of each individual's foot (Lucas *et al.*, 2014). Additional research has identified that the distal attachment of the PP to the proximal phalanx is instead via two bundles that attached plantarly on either side of the phalangeal articular surface, creating a "socket" for the MT head (Barlow,

1943; Deland *et al.*, 1995; Gregg *et al.*, 2007a; Kelikian *et al.*, 2011). Sarrafian (2011) identified the thick bundles as the “ill defined” short sesamophalangeal ligaments, attaching proximally to their respective HS, and distally to “the base” of the proximal phalanx (Kelikian *et al.*, 2011). The PP been more explicitly designated the sesamophalangeal ligaments (Linklater, 2012). The two sesamophalangeal ligament bundles are said to give strength to the medial and lateral edges of the PP distally, leaving the central component between them thinner (Dereymaeker *et al.*, 2011; Gregg *et al.*, 2007a; Johnston *et al.*, 1994); this was also noted in the PP of the less, non-sesamoid supported toes. Reports also suggest that the central component of the hallucal PP, between the two sesamophalangeal ligaments, contains a transverse band of tissue (Barlow, 1943; Dereymaeker *et al.*, 2011). The proximal part of the band extended from between the two sesamoids; but it is unclear whether it contributes to the intersesamoid ligament or is considered a different structure. This thinner component has been identified by some as a meniscus (Dereymaeker *et al.*, 2011), but most describe it as being part of the PP (Kelikian *et al.*, 2011; Lucas *et al.*, 2014). This component alone has been thought to play a role in the stability to the first MTPJ (Dereymaeker *et al.*, 2011; Lucas *et al.*, 2014), but is not consistently described and was hard to differentiate.

A thicker and more robust attachment of the PP to the proximal phalanx means nothing for the stability of the MTPJ if there are no equally strong connections to the first MT. The proximal end of the PP was thin and synovial (Deland *et al.*, 1995; Haines *et al.*, 1954; Lucas *et al.*, 2014),

suggesting importance in blood supply to the first MT head (Jones *et al.*, 1995; Schneider, 2013), but not for first MTPJ stability. There are, however, reinforcing elements described attaching the PP to the first MT head. Most of these attachments are described as converging into common bands prior to HS attachment (Kelikian *et al.*, 2011).

The Intersesamoid Ligament

During severe HV correction surgery and after sesamoidal trauma the intersesamoid ligament is often sectioned (Fiacco *et al.*, 2017), and as such knowing its exact anatomy and connections is vital for accurate targeting and reducing post-operative complications. The intersesamoid ligament is also implicated in other conditions of the foot such as turf toe, hallucal dislocations and intersesamoid ruptures (Capasso *et al.*, 1990; Jahss, 1980; McCormick *et al.*, 2009). The intersesamoid ligament is a structure rarely investigated, with ambiguities regarding “exact anatomy, location and definition” (Fiacco *et al.*, 2017). This is in part due to its involvement in several surrounding structures, such as the first MTPJ meniscus (Dereymaeker *et al.*, 2011), the FHL tunnel (Brenner *et al.*, 2002; Orr, 1918), the first MTPJ synovial capsule (Brenner *et al.*, 2002) or depending on the definition, different parts of the PP (Berquist, 2010; Kelikian *et al.*, 2011; Lucas *et al.*, 2014; Richardson, 1987). The intersesamoid ligament is made up of a set of transversely oriented collagen fibres spanning the space between the two HS and attaching to the medial aspect and the lateral aspect of the LS and MS respectively (Brenner *et al.*, 2002). This connection between the HS is a critical component of the

HS complex and integrity, and an indirect connection between any tendons and ligaments attaching to the HS (Brenner *et al.*, 2002; Fiacco *et al.*, 2017). The intersesamoid ligament keeps the HS at an average distance of 2-4mm from one another (Kewenter, 1936; Prieskorn *et al.*, 1993). Additionally the ligament has been measured to be an average of 3.03mm thick, with a longitudinal length of 8.66mm plantarly (Fiacco *et al.*, 2017) however the work measuring the ligament provides no real clear methodology and thus should be re-established before making any conclusions regarding relative strengths.

The integrity of the intersesamoid ligament is a key variable for the severity of the classification for turf toe dislocation injury, the ligament is undisrupted in the least severe type I dislocation, whereas the ligament is totally disrupted in the more severe types IIA and B (Anderson *et al.*, 2007; McCormick *et al.*, 2009). Specific cases illustrate this relationship. Intersesamoid ligament partial rupture has been reported in combination with transverse HS fracture (Jahss, 1980). Proximal and distal HS fragments were associated with the unruptured and ruptured intersesamoid ligament components, respectively (Jahss, 1980). From this, it has been theorised that strong distal attachment of the HS to the proximal phalanx via the sesamophalangeal ligaments (or PP) creates vulnerability under specific circumstances. When the first MTPJ is hyperextended to the point of HS dislocation which varies depending on the situation, with a normal range between 50°-90° dorsiflexion (Bojsen-Møller *et al.*, 1979; Durrant *et al.*, 2009; Hetherington *et al.*, 1990), additional stress is borne by the intersesamoid

ligament, leading to its rupture (Jahss, 1980). Transverse fracture of the LS provides a suggestion of the intersesamoid ligament strength, immobilising it amongst its other strong attachments, rather than failing and allowing further dislocation. The rupture of the intersesamoid ligament, when loaded in hyperextension, may be aided by the attachment of the PP to the distal border of the ligament (Cohen, 2009). Further evidence is provided in a case of a footballer rupturing their intersesamoid ligament, leading to a lateral dislocation of the LS. Interestingly, no other dislocation of MTPJ structures was reported (Capasso *et al.*, 1990). Repeated changes of direction combined with large compressive and shear forces applied to the hallux, such as during multi-directional sports, may lead to the isolated failure of the intersesamoid ligament, adding support to its role in resisting shear forces (Fiacco *et al.*, 2017).

After any disruption to the intersesamoid ligament, there tends to be a dislocation of the sesamoids out to either side of the first MT head (Anderson *et al.*, 2007; Capasso *et al.*, 1990; Jahss, 1980; McCormick *et al.*, 2009). Surgical reduction of HS dislocations are hampered by the avascular nature of the ISL (Sobel *et al.*, 1992), hence a reliance on synthetic materials (Anderson *et al.*, 2007; Capasso *et al.*, 1990; McCormick *et al.*, 2009). The disruption of the intersesamoid ligament has its most obvious effects on the positions of the sesamoids, but may not be limited to HS dislocations. Dorsally, the intersesamoid ligament interacts with a large synovial pad that lines the first MTPJ joint cavity, and as such the ligament is articular, and articulates with the first MT head at the level of the intersesamoid crest

(Brenner *et al.*, 2002). On the plantar aspect of the intersesamoid ligament, the ligament itself is said to form the roof of the FHL tunnel and act as a pulley against which the FHL tendon runs (Nery *et al.*, 2017; Williams *et al.*, 2009b). The distal component of the intersesamoid ligament has been said to attach to the proximal portion of the PP (Cohen, 2009). Alternatively, the ligament has been said to be a component of the PP (Richardson, 1987). An oblique meniscus, between the HS on the articular surface of the ligament, has been reported (Dereymaeker *et al.*, 2011). It is unclear to what extent this meniscus interacts with the intersesamoid ligament (Dereymaeker *et al.*, 2011) and was not described elsewhere in the reviewed literature. The deep transverse metatarsal ligament (DTMTL) was reported to interact with the FHL tunnel and PP, as was the plantar aponeurosis, in addition to interactions directly with the HS (Haines *et al.*, 1954; Nery *et al.*, 2017) (Haines *et al.*, 1954; Valvo *et al.*, 1987). Disruption of the intersesamoid ligament may place additional strain on all of these interactions. Ultimately, a disruption to the intersesamoid ligament affects the entirety of the first MTPJ complex. Further consideration of other first MTPJ stabilisers is therefore warranted.

Hallucal Collateral Ligaments

Hallucal collateral ligaments are reported to bilaterally connect to the HS and PP. Medial and lateral collateral complexes are reported to attach dorsally to the medial and lateral epicondyles of the first metatarsal on their respective sides (Deland *et al.*, 1995; Kelikian *et al.*, 2011; Schneider, 2013).

Each collateral complex consisted of two ligamentous components that are difficult to distinguish from one another, and so are differentiated by their distal attachment sites (Deland *et al.*, 1995; Kelikian *et al.*, 2011; Nery *et al.*, 2017; Richardson, 1987; Schneider, 2013) and can be termed the *metatarsosesamoid suspensory* and the *metatarsophalangeal collateral ligaments* (Kelikian *et al.*, 2011; Nery *et al.*, 2017; Schneider, 2013). They are analogous to the collateral ligaments of the lesser toes (Deland *et al.*, 1995; Gregg *et al.*, 2007a; Nery *et al.*, 2017). Their structure and naming is ambiguous throughout the literature (Boike *et al.*, 2011; Dedmond *et al.*, 2006; Leventen, 1991; McCormick *et al.*, 2010; Richardson, 1987; Richardson, 1999), , have been confused as parts of the MTPJ capsule (Jahss, 1981), and, when identified, were named and described inconsistently.

The *metatarsosesamoid suspensory ligaments* were reported as the principal connections of the PP and HS to the MT head. They were considered essential for maintaining HS and PP position relative to the MT (Boike *et al.*, 2011; Nery *et al.*, 2017). The plantar/distal attachment for the *metatarsosesamoid suspensory ligament* was described as being along the associated medial or lateral margin of the PP or HS, with no precise data available (Lin *et al.*, 1996; Schneider, 2013). The ligament was fan-shaped with the distal attachment to be greater than the proximal attachment site on the first MT epicondyles (McCormick *et al.*, 2009; Schneider, 2013). The more posterior fibres run in a near vertical plantar direction onto the PP of associated HS margin, and the anterior fibres run obliquely towards the distal

aspect of the associated PP medial or lateral margins (Kelikian *et al.*, 2011; Nery *et al.*, 2017; Richardson, 1987).

The *metatarsophalangeal ligament* was described as running obliquely along the respective medial and lateral sides of the collateral complexes. The posterior fibres were difficult to differentiate from the anterior fibres of the metatarsosesamoid suspensory ligament but were said to be distinguishable by their distal attachment sites on the tubercles on either side of the base of the proximal phalanx (Kelikian *et al.*, 2011; Richardson, 1987). However, this description was far less precise than it may seem; with multiple tissues converging on the tubercles, this alone cannot differentiate these ligaments (Deland *et al.*, 1995; Linklater, 2012; Nery *et al.*, 2017; York *et al.*, 2017). The collateral ligaments of the first MTPJ were the means the HS and the PP were anchored to the MT, helping tighten up the connection that the HS or PP have with the proximal phalanx and thus stabilising the MTPJ as a whole. As the numerous descriptions attest, there is no accurate consensus as to how these vital ligaments attach plantarly.

Plantar Aponeurosis

On the plantar surface of the foot, the PA provides support to the foot as a whole (Chen *et al.*, 2014; Hicks, 1954) and is vital in maintaining longitudinal arch stability (Chen *et al.*, 2014; Hicks, 1954; Kogler *et al.*, 1996; Sarrafian, 1987), spanning from the posterior aspect of the medial tuberosity of the calcaneus and extending into the forefoot, where it is said to split into 5

digital bundles (Chen *et al.*, 2014; Hicks, 1954). At the level of the first MT head the PA is made up of a deep and superficial layer. The deep layer is a direct extension of the longitudinal fibres of the PA, advancing distally toward the PP and HS. The superficial layer extends superficially towards the dermis at the ball of the foot and becomes a lattice of non-specific fibres (Chen *et al.*, 2014) with a more transverse orientation forming the superficial transverse MT ligament (Chauveaux *et al.*, 1987; Haines *et al.*, 1954). The superficial transverse MT ligament is said to resist transverse force at the plantar bases of the proximal phalanges, but it did not directly attach to the PP or MT bones (Haines *et al.*, 1954; Morton, 1922). No relevant biomechanical data were identified in the reviewed literature.

In the first ray of the foot, the longitudinal deep fibres of the PA split on either side of the long flexor tendon into digital bands (Haines *et al.*, 1954; Hicks, 1954). These digital bands are said to attach to the proximal-most point of the PP or HS (Do Carmo *et al.*, 2008; Kelikian *et al.*, 2011; Samojla, 1994), but are also described as attaching onto the medial and lateral sides of the proximal most edge of the PP or HS (figure 1.2.2C; (Haines *et al.*, 1954), similar to the PP of the lesser toes (Deland *et al.*, 1995). Haines (1954) found the digital bands to differ from each other, with the most medial in the first ray being strongest. (Haines *et al.*, 1954) These were assumptions without any tensile failure properties being investigated. Some research has investigated load bearing and failure points of these digital bands collectively, but not individually, finding that they can bear up to 3.4 times body weight (Chen *et al.*, 2014; Hicks, 1954; Kitaoka *et al.*, 1997). Additional research into

the digital bands to the HS could elucidate any differences between sesamoids in relation to their roles in longitudinal arch stability. This could be done by measuring the interaction of the PA digital bands with their respective sesamoids. Haines (1954) also identified that the medial digital band attached distally to the medial sesamoid and then onto the *conjoined tendon*, described as the tendons of the abductor hallucis muscle and the tendon of the medial head of the FHB muscle. This conjoined tendon is said to reach the proximo-medial side of the proximal phalanx (Haines *et al.*, 1954). Similarly, the lateral digital band was reported to attach to the LS, before continuing distally to the lateral plantar aspect of the base of the proximal phalanx. Together, the lateral and the medial bands created a bridge of aponeurosis over the long flexor tendon, creating the plantar surface and entrance to the long flexor tunnel between the HS (Haines *et al.*, 1954; Valvo *et al.*, 1987). The makeup of the long flexor tunnel has only been investigated in passing, despite its intimate interaction with the HS. Work by Hedrick states a contribution to the long flexor tunnel from the superficial longitudinal tracts of the superficial layer giving sagittal septae from their deep surfaces. These are said to form the arches for the entrances of the flexor tendons and attach into the tendon sheaths. The connections from these sagittal septae are reported to be numerous, including the fascia of the transverse head of the adductor hallucis, the DMTL, as well as the PPs and collateral ligaments of the MTPJs. Importantly these sagittal septae are said to attach into the HS (Figure 1.2.3)

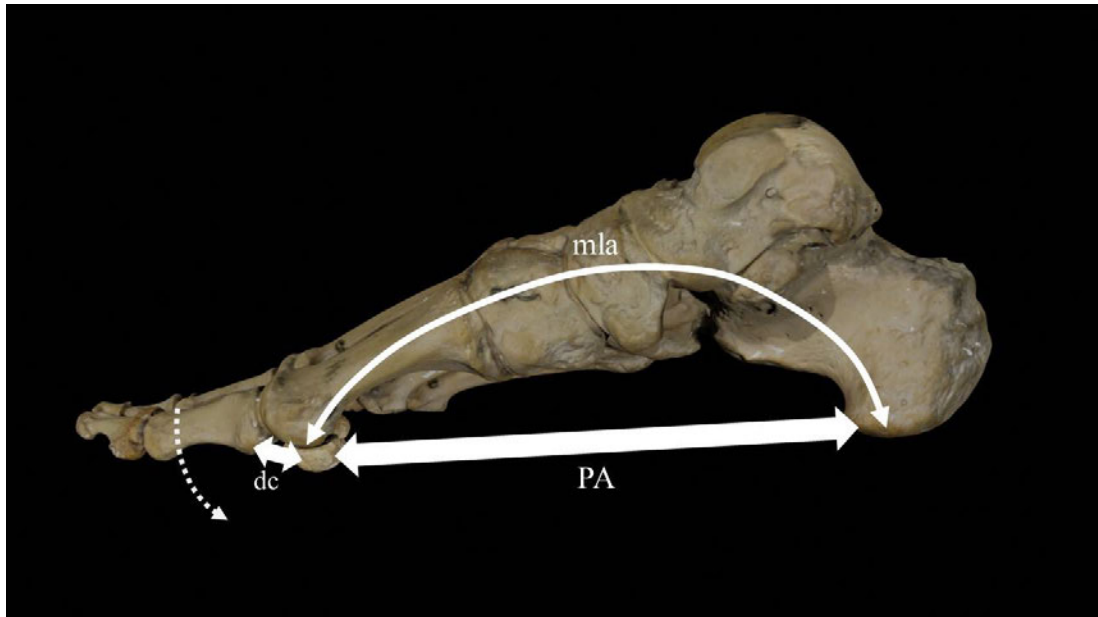


Figure 1.2.3. Medial view of an osseous foot: the plantar aponeurosis (PA) said to connect the calcaneus to the proximal phalanx. Supporting the medial longitudinal arch (mla). At the distal end of the PA, at the distal connection (dc) the attachment to the proximal phalanx is said to be direct (Haines *et al.*, 1954), or through conjoined tendons of other structures including the HS or PP (Do Carmo *et al.*, 2008; Haines *et al.*, 1954; Hedrick, 1996). The tightening of the PA creates a windlass effect that pulls the proximal phalanx into flexion (dotted arrow), and raises the mla (Hicks, 1954).

And the heads of the FHB (Hedrick, 1996). How the HS are interacting with the PA has not been elucidated.

Connection of the calcaneus to the HS is provided by the PA, and has been considered essential for longitudinal arch support (Hicks, 1954) (Figure 1.2.3). The “tie-rod”, that the PA represents, is integral to the deep osseous stability of the foot during weight bearing (Aquino *et al.*, 1999; Bojsen-Moller *et al.*, 1976; Hicks, 1954). This weightbearing-reactive “tie-rod” creates the “windlass effect” (Hicks, 1954). Due to the PA attaching into the proximal phalanges via the PP or the HS in the first ray, and via the PPs in the lesser toes, there is a pull on the proximal phalanges towards plantarflexion during weight bearing (Hicks, 1954). The weight spreads the longitudinal arch longitudinally, tightening the PA. However, when the first ray or any lesser rays are brought into dorsiflexion, the PA will tighten and, especially when not under load, the longitudinal plantar arch will elevate as it shortens in length (Aquino *et al.*, 1999; Chen *et al.*, 2014; Hicks, 1954; Kogler *et al.*, 1996). In contrast, a study demonstrated no change in the longitudinal arch when first ray PA connections were sectioned (Chen *et al.*, 2014). Previous research has similarly shown little impact when sectioning the medial aspect of the PA, but these studies did not target the slips to the sesamoids specifically (Huang *et al.*, 1993; Murphy *et al.*, 1998; Thordarson *et al.*, 1997). A firm connection between the PA and the FHB was also reported (Chen *et al.*, 2014); this connection to a muscular component could provide additional proximal stability to the PP or HS, and was observed to elevate the foot arch when the PA was tightened by acting on the toes. A direct correlation between FHB

strength and medial longitudinal arch height in an elderly population was also reported (Fukumoto *et al.*, 2020). This research may explain why when sectioning the first digital bundle of the PA, the arch was not severely impacted (Chen *et al.*, 2014) and suggests that further research in musculotendinous and other soft tissue interactions of the first ray is needed.

Flexor Hallucis Brevis Muscle

The most cited interaction that the HS have with any muscle is with the FHB (Agawany *et al.*, 2010; Arakawa *et al.*, 2003; Athanasiou *et al.*, 1998; Brenner, 1999; de Britto, 1982; Dedmond *et al.*, 2006; Feldman *et al.*, 1970; Inge *et al.*, 1933; Jahss, 1981; Kelikian *et al.*, 2011; Lucas *et al.*, 2014; Richardson, 1999; Van Hal *et al.*, 1982). The lateral head tendon of the FHB is said to interact with the LS and the medial head tendon of the FHB with the MS. This is a consensus within the literature (Kelikian *et al.*, 2011). However, authors diverge in opinion on the nature of the interaction. The most common description of the HS in relation to the FHB is that the HS are embedded within the respective tendons of the FHB (Figure 1.2.2.B; (Anwar *et al.*, 2005; Athanasiou *et al.*, 1998; Dedmond *et al.*, 2006; Feldman *et al.*, 1970; Inge *et al.*, 1933; Jahss, 1981; Lucas *et al.*, 2014; Powers, 1934; Richardson, 1999; Scranton *et al.*, 1980; Van Hal *et al.*, 1982), which continue distally to attach onto the medial and lateral plantar tubercles of the proximal phalanx respectively (Nery *et al.*, 2017; Orr, 1918). This description is most often accompanied with the comparison of the HS with the patella. This association with the patella makes sense as they are both sesamoids and can be seen to work in a similar way biomechanically (Aper *et al.*, 1996). In more

contemporary research, the patella has been shown to attach with distinct footprints to a number of separate tendons and ligaments (Kruckeberg *et al.*, 2018). Similar findings have been made regarding the HS (Agawany *et al.*, 2010; Leventen, 1991; Schneider, 2013), making the description of embedded HS in the FHB tendon heads too simplistic. To glean an understanding of whether the HS are “embedded” in the FHB tendons, an observation of the development of the HS proves useful. The HS are described as identifiable from 8 weeks *in utero* and are intimately related to the periosteum of the first MT, which, by the 12th week, is recognisable as the first MTPJ capsule (Inge *et al.*, 1933). At around 12-16 weeks the FHB tendon can be seen to invest into the plantar aspect of the HS (Inge *et al.*, 1933). Brenner *et al.* (Brenner *et al.*, 2002) confirm this plantar and proximal attachment of the FHB, as well as observing the intimate relationship of the HS with the first MTPJ capsule. Additionally, the abductor and adductor hallucis tendons are said to pass by, with “some inner fibres” attaching to the HS plantar sides. These studies provide an understanding that the HS do not develop within the FHB tendons, and so are not “embedded” within them, but rather are attached to, by them.

The concept of the HS being embedded in the FHB or attached to by a number of other structures differs from the opinion that the HS are embedded within the PP, as discussed previously (de Britto, 1982; Haines *et al.*, 1954). Alternatively, the FHB tendons attach to their respective HS, as well as continuing distally to contribute to the deep part of the proximal PP (Kelikian *et al.*, 2011; Lucas *et al.*, 2014; Richardson, 1987; Theumann *et al.*, 2002),

with descriptions varying based on varied definitions of PP borders. More detailed studies of HS attachments reject the idea of the sesamoids being fully enveloped within the FHB tendinous heads. Rather, it was inferred that the FHB tendinous heads had an attachment proximally and plantarly on their respective HS. (Agawany *et al.*, 2010; Arakawa *et al.*, 2003; Brenner, 1999; Brenner *et al.*, 2002; Kelikian *et al.*, 2011; Leventen, 1991; McBride, 1928; Owens *et al.*, 2001; Pretterklieber, 1990; Schneider, 2013; Theumann *et al.*, 2002). These studies lack quantitative data and clear descriptions, making comparisons difficult. Despite the paucity of accurate information regarding the FHB attachments to the HS, there are reports of its interactions with other surrounding tissues that provide a more complete picture. As previously mentioned the FHB has been observed firmly attaching with the PA bundle to the first ray, implicating it in the windlass mechanism, which by definition means that it connects to the PP or the HS to act upon the proximal phalanx (Chen *et al.*, 2014; Fukumoto *et al.*, 2020). The role of the FHB in the medial longitudinal arch suggest that the FHB tendons attach to the HS or surrounding tissues in a meaningful way, to act effectively onto the base of the proximal phalanx. There are additional structures identified to act on the base of the proximal phalanx of the hallux that have been said to both interact with the HS and the FHB tendons. These are the tendons of the adductor hallucis and abductor hallucis muscles, said to engage with the tendons of the lateral and medial FHB heads respectively (Brenner, 1999; Chen *et al.*, 2014; McBride, 1928; Owens *et al.*, 2001; Young *et al.*, 2020). Some anatomical studies have identified the tendon of the medial head of the FHB fusing with the deep fibres of the tendon of the abductor hallucis tendon

at about the width of one finger proximal to the MTPJ line (Brenner, 1999; Wong, 2007). However, this fusing of the abductor hallucis tendon to the medial head of the FHB was either not observed in other studies (Theumann *et al.*, 2002), or only identified as minor fibrous slips in a small percentage of the sample population (3 of 15 dissected feet; (Agawany *et al.*, 2010).

The adductor conjoined tendon was said to converge and interdigitate with the tendon of the lateral FHB at the level of the LS (Kelikian *et al.*, 2011; McBride, 1928; Owens *et al.*, 2001; Valvo *et al.*, 1987). Other research suggested no interaction between the two at all (Theumann *et al.*, 2002). Interaction between the adductor hallucis tendon and the FHB lateral head tendon is similar to descriptions of the medial side with the abductor hallucis tendon (Brenner, 1999; Wong, 2007). A common theme is seen, where the respective lateral and medial aspects of the lateral and medial sesamoids lack clear, consistent, qualitative, or quantitative data for the interactions that they have with incoming tendons of the adductor and abductor hallucis muscles.

The reviewed literature described the incoming attachments to the HS to be mainly enveloped in the FHB, when not embedded within the PP. This statement is added to with a mention of the adductor and abductor hallucis distal tendons attaching in varying degrees of importance to their respective HS (Anwar *et al.*, 2005; Athanasiou *et al.*, 1998; Dedmond *et al.*, 2006; Inge, 1936; Jahss, 1981; Lucas *et al.*, 2014; Richardson, 1999; Scranton *et al.*, 1980). This common description is one that is difficult to reconcile. Are the

sesamoids embedded/enveloped, or are they attached to by other structures? These questions have partially been answered by previously discussed research, suggesting that the abductor and adductor hallucis tendons may attach directly to the HS, a concept supported by developmental research (Agawany *et al.*, 2010; Brenner *et al.*, 2002; Owens *et al.*, 2001; Theumann *et al.*, 2002; Wong, 2007).

Abductor Hallucis Muscle

The medial aspect of the MTPJ sees a potential set of interactions between the incoming tendons of the FHB medial head, the abductor hallucis as well as passive structures such as the medial collateral ligament, the medial capsule, and a slip from the first bundle of the PA (Kelikian *et al.*, 2011). The most medial and visible of these structures is the abductor hallucis muscle and its tendon. The tendon is said to twist to attach onto the medial and plantar margins of the MS and surrounding PP, or to bypass the MS entirely to distally attach to the base of the proximal phalanx. There were variations thereof that made up to four different types of attachment (Agawany *et al.*, 2010; Brenner, 1999; Kelikian *et al.*, 2011; Schwagten *et al.*, 2020; Wong, 2007). Brenner (1999) described three types that best encompass variations, where the amalgamated tendons of the FHB and abductor hallucis attach distally, either to the proximal phalanx alone (Type A), to both the proximal phalanx and MS (type B), or to the MS alone (type C) (Brenner, 1999), with 59.6% of the sample to be of type B. Whereas Agawany and Meguid (2010) identified the dominant type (46.7%) to be more

akin to type A, with no connection to the MS (Agawany *et al.*, 2010; Brenner, 1999). Depending on the attachment type, the abductor hallucis muscle serves to pull onto the PP and/or the medial tubercle of the proximal phalanx via the “conjoined tendon” to abduct the MTPJ. It has been said that some of the superomedial fibres connect superiorly to the transverse lamina of the extensor hood and act upon it (Pfeffer *et al.*, 2017). This is alluded to by other research finding that the extensor hood cannot be differentiated from the MTPJ capsule, and that the abductor hallucis muscle was attached into the medial aspect of the MTPJ capsule (Theumann *et al.*, 2002; Valvo *et al.*, 1987). This connection to the extensor apparatus would imply the structures are damaged in hallux valgus, as the abductor hallucis tendon was pulled plantarly, and the bunion growth stretched the medial aspect of the MTPJ capsule (Brenner, 1999). Further research into these connections would advance the understanding of the pathomechanisms and treatments of this deformity.

Adductor Hallucis Muscle

On the lateral side of the hallux, the adductor hallucis muscles, with their transverse and oblique heads, are said to merge together into a short tendon at the level of the first MT neck (Theumann *et al.*, 2002). This short tendon is described as attaching to the lateral aspect of the LS, then continuing distally to attach to the lateral plantar base of the proximal phalanx (Kelikian *et al.*, 2011; McBride, 1928; Owens *et al.*, 2001; Theumann *et al.*, 2002). The oblique head has been found to have three components at its

distal end, each passing dorsal to the first DTMTL: the medial component, attached laterally, and the central component, attached more plantarly. Both were attached onto the margins of the LS and surrounding PP. The lateral component is said to have a broad attachment to the LS as well as to the base of the proximal phalanx, with fibres that can be traced as a “definite band” going straight to the proximal phalanx (Kelikian *et al.*, 2011). However, others found that there were no separate phalangeal attachments from the lateral component of the oblique head (Owens *et al.*, 2001). or that the oblique head (OH) had three components (Valvo *et al.*, 1987). These were attached to the LS, to the plantar aspect of the LS, and to both the LS and the proximal phalanx (Valvo *et al.*, 1987). It was further suggested that the transverse head attached onto the extensor aponeurosis and also had a component that combined with the oblique head to attach to the lateral sesamoid, terminating on the FHL tunnel (Kelikian *et al.*, 2011; Valvo *et al.*, 1987). Most surgical texts are in general agreement with this description albeit in less detail, describing the adductor hallucis tendon as attaching to the LS and the proximal phalanx (Kelikian *et al.*, 2011; Lin *et al.*, 1996; Owens *et al.*, 2001; Schneider, 2012; Wulker, 2000).

The details of whether the oblique head and transverse head tendons both attach to the lateral sesamoid are ambiguous within the literature, with suggestions of the distal attachment being the proximal phalanx alone (Coughlin, 1996). This representation is a common sight diagrammatically (Austin *et al.*, 1981; Coughlin, 1996; Joplin, 1950; Mann, 1986; McBride, 1928; Miller, 1975; Resch *et al.*, 1989; Schneider, 2012). However some

research identifies the LS as the most common distal attachment site for both the transverse and oblique tendons of the adductor hallucis muscle (Arakawa *et al.*, 2003).

The joining of the tendons from both adductor hallucis heads, as well as the joining of the FHB lateral head, has given rise to the agglomeration being called a conjoined tendon (Kelikian *et al.*, 2011; Owens *et al.*, 2001).

The description of *conjoined tendons* on both sides of the MTPJ was ambiguous in the literature. Should they be considered PP or separate tendons? This was of interest in a case of lateral release of the *lateral conjoined tendon* to correct hallux valgus leading to hallux varus as an iatrogenic sequelae (Owens *et al.*, 2001).

To put these soft tissue releases into context, early authors stated that the cause of hallux valgus was the contracture of the conjoined tendons of the adductor hallucis muscle heads and FHB muscle, drawing on their attachment to the proximal phalanx (McBride, 1928; Silver, 1923). Their release was suggested to permit the proximal phalanx to be realigned with the MT head (Coughlin *et al.*, 2013; Mann, 1990; McBride, 1928). As a result of this belief, the main targeted lateral structures are the adductor hallucis muscle tendons, the lateral joint capsule of the first MTPJ and the first DTMTL (Coughlin *et al.*, 2013; Mann, 1990; Schneider, 2013; Wulker, 2000). This principle of balancing the structures around the MTPJ also applies to traumatic HV, conditions like turf toe, where medial stabilising structures are

traumatically damaged, and so the “imbalance” needs to be rectified using the same or similar surgeries (McCormick *et al.*, 2009, 2010)

McGlamry’s surgical textbook states that “the adductor tendon is the first of the deforming structures to be evaluated and released” for hallux valgus correction surgery (Southerland *et al.*, 2012), and other surgical textbooks are of the same opinion (Coughlin *et al.*, 2013; Pfeffer *et al.*, 2017). Adequate exposure and an understanding of the anatomy of the distal attachments of the adductor hallucis muscle heads are vital in their safe targeting during this lateral soft tissue release (Sammarco, 2008; Southerland *et al.*, 2012; Valvo *et al.*, 1987). Since most surgical texts describe distal soft tissue procedures to include an adductor tenotomy, it is vital to understand how to target the adductor hallucis conjoined tendon, which requires clearer understanding of the precise anatomy. The oblique and transverse heads are suggested (Sammarco, 2008), but there were no described distinctions for other neighbouring attachments to the proximal phalanx or LS (Lin *et al.*, 1996; Mann, 1990; Southerland *et al.*, 2012).

This lack of specificity when releasing the abductor hallucis was found to be unpredictable (Lin *et al.*, 1996), with a large percentage of adductor tenotomies failing to transect the targeted structures whilst unintentionally damaging other structures (Lin *et al.*, 1996). This unpredictability could lead to unwanted outcomes from releasing other lateral tissues such as the FHB or the sesamophalangeal ligament, or even damaging the articular cartilage on the first metatarsal head (Hawkins, 1971; Joplin, 1950; Lin *et al.*, 1996;

Owens *et al.*, 2001). As previously mentioned, one of the other targeted structures during these soft tissue releases is the first DTMTL (Coughlin *et al.*, 2013; Mann, 1990; Schneider, 2013; Wulker, 2000), which is the final structure identified to interact with the HS to be reviewed.

Deep Transverse Metatarsal Ligament

The first deep transverse metatarsal ligament (DTMTL) is biomechanically described as being part of a series of four broad DTMTLs that connect all the plantar plates to one another, and thus their respective MT heads via the collateral ligaments. Together they create the “transverse tie-bar” of the forefoot, which resists excessive splaying and controls the position of the forefoot in response to load (Samojla, 1994; Stainsby, 1997). The DTMTL is said to be “clearly concerned” with the proper alignment of the metatarsal heads (Haines *et al.*, 1954). The first DTMTL has been shown to be vital in maintaining distal intermetatarsal distance, conserving first MTPJ stability and anchoring the sesamoids (Abdalbary *et al.*, 2016; Kura *et al.*, 1998; Stainsby, 1997).

The first DTMTL is identified as reaching the lateral margin of the LS (Brenner *et al.*, 2002; Richardson, 1987; Theumann *et al.*, 2002) or first MTPJ PP (Haines *et al.*, 1954; Nery *et al.*, 2017), dependent upon what each author outlines as the PP. The first DTMTL was described as a fibrous connection between the lateral sesamoid and the plantar plate of the second MTPJ (Schneider, 2013), either with two heads (Alvarez *et al.*, 1984; Valvo *et*

al., 1987), or a single component (Barg *et al.*, 2012; Coughlin *et al.*, 2013; Schneider, 2013). The medial attachment of the first DTMTL was commonly described as being plantar on the lateral aspect of the LS and/or the PP, with no additional detail. The description was similarly vague for the lateral attachment, being to the medial border of the second MTPJ PP (Haines *et al.*, 1954; Kelikian *et al.*, 2011; Richardson, 1987; Valvo *et al.*, 1987).

The contention within the literature about the presence of a second head for the first DTMTL has some serious implications (Alvarez *et al.*, 1984; Valvo *et al.*, 1987). The second head was described as attached laterally to the second MT PP but its medial attachment was dorsal onto the first MT head, merging into the lateral margin of the MTPJ capsule and lateral collateral ligament complex (Alvarez *et al.*, 1984; Valvo *et al.*, 1987). The dorsal component of the first DTMTL was likely to have a role in maintaining the intermetatarsal distance, as well as preventing first MT internal rotation. It was believed to be one of the contracted structures during HV that should be incised to reduce the HS medially, plantar to the first MT head (Valvo *et al.*, 1987). When dorsal and plantar DTMTL components were identified, the conjoined adductor hallucis tendon was found consistently between them (Alvarez *et al.*, 1984; Valvo *et al.*, 1987). This relationship with the adductor hallucis tendons suggests that the dorsal component is invariably cut during soft tissue procedures targeting these tendons, especially when taking a dorsal surgical approach (Lin *et al.*, 1996; Valvo *et al.*, 1987). Most surgical texts do not mention this dorsal component at all.

During hallux valgus repair, and the associated soft tissue releases, the main targeted lateral structures are the adductor hallucis muscle tendons, the lateral joint capsule of the first MTPJ, as well as the first DTMTL (Coughlin *et al.*, 2013; Schneider, 2013). During the development of hallux valgus, the first MT is said to deviate medially, whereas the sesamoids, that usually sit directly plantar to the MT, are said to remain in position. This is purportedly due to their attachment to the first DTMTL and the adductor hallucis tendons along the plantar lateral aspect of the LS (Schneider, 2013). The continued fibres of both lateral structures are described as attaching onto the proximo-lateral end of the proximal phalanx, which, during hallux valgus, produces a deforming force pulling it proximo-laterally. This, in turn, is said to push the first MT head further medially (Schneider, 2013). Both the anchoring of the sesamoids and the deforming forces producing hallux valgus are why these structures are targeted during soft tissue releases (Schneider, 2013). A good knowledge of the anatomy of any targeted structure, including the first DTMTL, is necessary in its safe and successful sectioning during soft tissue releases, such as those carried out during most hallux valgus correction procedures. A poorly carried out procedure can lead to avascular necrosis, overcorrection and instability (Schneider, 2013; Valvo *et al.*, 1987; Wang *et al.*, 2015).

1.2.4 Conclusion

This review of the literature has highlighted the ambiguities relating to most of the named structures interacting with the hallucal sesamoids, a great number of these structures are disrupted and targeted during surgical treatments of conditions affecting the hallucal sesamoids. Since the interactions of many of these structures are reported as vague or as contradicting within the literature, current surgical targeting techniques cannot be based on accurate anatomical data, and as such a likely to have unwanted iatrogenic outcomes known or unknown to the operator. Further research is needed to understand the attachments and relationships of incoming tendons and ligaments that are often the target, wanted or not, of surgical intervention. A precise, detailed, and reproducible description of this complex anatomy may facilitate a true anatomical repair for hallux valgus and related disorders.

1.2.5 References

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Part One, Chapter Three

1.3 Hallucal Sesamoid Absence and Partism

The hallucal sesamoids (HS) do not only differ from each other but differ between individuals. Amongst the range of variations reported are partism and absence of the sesamoids (Inge, 1936; Inge *et al.*, 1933). Absence of the sesamoids was considered rare and was only reported 23 times in the reviewed English language literature (Table 1.3.1). One study identified three individuals with an absent sesamoid out of a sample of 1032 patients, showing an incidence of 0.29% (Karadaglis *et al.*, 2003). In 60.8% of cases reviewed sesamoid absence was either bilateral (Alshryda *et al.*, 2012; Day *et al.*, 2002; DuVries, 1959; Helal, 1981; Mason *et al.*, 2012; Shtofmakher *et al.*, 2014; Wright, 1998; Young *et al.*, 2020) or there was a smaller, underdeveloped, or partite, corresponding sesamoid contralaterally (Inge, 1936; Karadaglis *et al.*, 2003; Le Minor, 1999; Shtofmakher *et al.*, 2014; Song *et al.*, 2013; Yildirim *et al.*, 2006). This tendency towards bilateral sesamoidal deformation suggests a genetic component, and as such, the absence was often described as congenital. Unfortunately, the reports were so rare that further investigations with parents or progeny were not identified.

Absence of a sesamoid has been suggested as the result of an insult, leading to avascular necrosis and resorption (Berquist, 2010; Song *et al.*, 2013). One case reported a medial sesamoid (MS) progressively collapsing and demineralising over the course of a year (Berquist, 2010; Song *et al.*, 2013). The resulting MS barely appeared in radiographs, and early in the

Table 1.3.1- Table of the literature reviewed, outlining the number of cases, the side and position of the affected hallucal sesamoids, the symptoms and any pertinent notes from the papers. This table highlights the rarity and inconsistent reports of hallucal sesamoid absence.

Authors	Year	Case(s)	Age/Sex	Medial Sesamoid	Lateral Sesamoid	Asymptomatic/ Symptomatic	Notes
(Inge 1936)	1936	2	28/M 33/F	Case 1:Left side absent Case 2:Left side absent		Asymptomatic “no functional disturbances”	“The MS on the right sides were diminutive in size”
(Lapidus 1939)	1939	1	30/F	Right side absent		Weakness and occasional pain in both feet	Moderate pronation in both feet “Failure to ossify”
(Hubay 1949)	1949	1	22/M	Left side absent			
(DuVries 1959)	1959*	1		Both sides absent	Both sides absent		
Helal (Helal 1981)	1981	1		Both sides absent	Both sides absent		“the author has seen one adult with congenital absence of both sesamoids”
(Zinsmeister and Edelman 1985)	1985	2	24/F 55/F	Case 1:Right side absent Case 2: Right side absent		Both patients symptomatic with HV	First case: Vestigial left MS, no cartilaginous pre-cursor in right foot Second case: Absence in right MS, where cartilaginous pre- cursor was found.
(Goez and DeLauro 1995)	1995	1	50/F	One side absent		HV	
(Wright 1998)	1998	1	19/F	Both sides absent	Both sides absent	Bilateral HV	The patient had been a premature baby (7 months) and had hip dysplasia.
(Jeng et al. 1998)	1998	1	47/F		Left side absent	Pain under 1 st MT head	Pain after 2 days of strenuous exercise, normal range of motion, pain when passively extending Hallux, focal area of calcification where LS should be, “attempt at ossification.”

(Le Minor 1999)	1999	1	47/F		Right side absent	Asymptomatic, trauma of the ankle	Left side LS was “extremely reduced” Absence of grooves and crista on both sides, with normal function.
(Day et al. 2002)	2002	1	57/F	Both sides absent		Asymptomatic, unrelated stress fracture of the 2 nd MT head.	Incidental finding, statement was ambiguous: “a contralateral view confirmed the absence of the tibial sesamoid”.
(Karadaglis and Grace 2003)	2003	3		Absent in 3 feet	Absent in 1 foot	No mention of symptoms, as it was a retrospective study.	Large study on partism, no focus on absence, MS absent in 3 and hypoplastic in 1, LS absent in 1 and hypoplastic in 3, 1 case had bilateral absence of a HS.
(Kanatli et al. 2006)	2006	1	17/M	Right side absent		Pain under first MTPJ of right foot	No evidence of cartilaginous precursor, normal FHB attachments, normal crista and grooves. “Loss of underlying cushion (MS) may cause imbalance under associated MT head leading to localised pain”
(Yildirim and Saygi 2006)	2006	1	18/M		Left side absent	Pain under first MTPJ of left foot, moderate amount of HV but not symptomatic.	Bipartite MS in left foot, normal FHB attachment to the proximal phalanx. Right foot had an unusually small LS. MRI identified cartilaginous precursor.
(Williams et al. 2009)	2009	1	21/M	Left side absent	Left side absent	Activity related metatarsalgia with tenderness under the first MTPJ	5 years of increasing pain, worsened during toe off at around 45 degrees dorsiflexion, no HV and no sesamoid in tendon (MRI) normal crista but no sulci. Pain from bursitis from abnormal kinematics, orthotic reduced pain by 75%.
(Berquist 2010)	2010	1	M		Right side absent	Chronic pain under 1 st MT head	Long distance runner, with small “remnant” of LS, “resulting from avascular necrosis and bone resorption”
(Alshryda et al. 2012)	2012	1	18/F	Both sides absent	Both sides absent	Severe bilateral HV with right side worse than left and heel pain since the age of 11 years	Rudimentary crista
(Mason et al. 2012)	2012	1	49/M	Left side absent	Both sides absent	Left HV	“Sesamoid absence would have predisposed the foot to HV” due to weaker medial collateral ligament

(Song et al. 2013)	2013	1	33/F	Left side absent		Asymptomatic left foot	Pain for 1 year under first MTPJ of right foot, showing hypoplasia of right MS, showing that it had collapsed, demineralised in fragments due to avascular necrosis
(Lui and Tam 2013)	2013	1	23/M	Both sides absent	Both sides absent	Bilateral HV deformity with left bunion pain	Right hallux more pronated than left. Normal grooves and crista, nodes of cartilage in PP.
(Shtofmakher et al. 2014)	2014	1	38/F	Right side absent		Right foot plantar pain, exacerbated during exercise, localised over the HS.	Bipartite LS in left foot
(Young et al. 2020)	2020	1	53/F	Both sides absent		Asymptomatic	Bilateral bifurcation of FHB tendon, where the medial FHB tendon crossed to the lateral aspect of the FHB and LS. Suggestion of a compensatory mechanism. Thickened plantar capsule.
(Zhang et al. 2020)	2020	2-3		Absence in 3 feet	Absence in 2 feet		Found as 3 feet in 150, no information regarding any of the cases, no side or sex or age details, on a Chinese Han population
Total reported		28-29 cases	Average age 34.1	32 total 9 bilat, 6 Left only, 5 Right only	20 total 8 bilat, 3 Left only, 2 Right only		

Abbreviations: MS: Medial Sesamoid, LS: Lateral Sesamoid, HS: Hallucal Sesamoid, MT: Metatarsal, MTPJ: Metatarsophalangeal Joint, FHB: Flexor Hallucis Brevis muscle, HV: Hallux Valgus.

necrosis the patient was asymptomatic, suggesting that some cases of HS absence share the same aetiology (Song *et al.*, 2013). Others have suggested the absence to be a failure of the primary mesenchyme differentiation for the HS, or a failure to ossify (Jeng *et al.*, 1998; Lui *et al.*, 2013; Williams *et al.*, 2009b; Wright, 1998). Since the HS ossify well after the commencement of ambulation, between 8 and 11 years of age, they can undergo stresses that prevent complete ossification and or create partism, leading to absence, or abnormally developed, or shaped sesamoids (Giori *et al.*, 1993; Kanatli *et al.*, 2006). With the advent of more readily available MR and CT scanning, clinical imaging of sesamoids has improved (Lui *et al.*, 2013; Mason *et al.*, 2012; Williams *et al.*, 2009b; Yildirim *et al.*, 2006; Young *et al.*, 2020). Absence of the sesamoids on otherwise normal radiographs, subsequent MR or CT imaging resulted in either a classification as cartilaginous nodes (Jeng *et al.*, 1998; Lui *et al.*, 2013; Yildirim *et al.*, 2006; Young *et al.*, 2020), or as a genuine absence of equivalent tissue (Kanatli *et al.*, 2006; Williams *et al.*, 2009b) in the MR or CT scan.. Alternatively, a bone scan or gadolinium-enhanced MRI allowed more detailed visualisation of the location of the missing HS and indicated avascular necrosis-associated absence (Julsrud, 1997; Song *et al.*, 2013). Some argued that the presence of normal crista and surrounding sulci on the first metatarsal indicated a failure to ossify (Jeng *et al.*, 1998; Le Minor, 1999; Yildirim *et al.*, 2006), whereas an absence of clear sulci with a rudimentary intersesamoid crest indicated a primary mesenchymal differentiation failure (Lui *et al.*, 2013). It was also stated that if the HS were missing, the sesamoid grooves and intersesamoid crest would not develop (Brenner *et al.*, 2002). These varying

reports provide a cross section of the information available to understand the aetiology of HS absence.

The current theories for what cause HS absence are threefold:

- Type 1- A primary mesenchymal differentiation failure early on during foetal development leaving a total absence of any sesamoidal tissue at the base of the hallucal head. As a result, the intersesamoid crest and sesamoidal grooves are ill-formed (Kanatli *et al.*, 2006; Williams *et al.*, 2009b).
- Type 2- A failure of ossification of a sesamoidal anlage, leaving a cartilaginous pre-cursor or a “thickened plantar plate”, with relatively normal appearing intersesamoid crest and sesamoid grooves. Caused by genetic or mechanical based mechanisms (Jeng *et al.*, 1998; Lui *et al.*, 2013; Williams *et al.*, 2009b; Wright, 1998; Yildirim *et al.*, 2006; Young *et al.*, 2020).
- Type 3- A degenerative HS that becomes fragmented and demineralised until completely absent radiographically, caused by a vascular insult leading to avascular necrosis. The insult may have a greater effect if the sesamoid has limited collateral supply and is already hypoplastic such as in type 2 (Berquist, 2010; Song *et al.*, 2013).

The absence of a HS was often said to be incidental, and individuals can be asymptomatic (Day *et al.*, 2002; Inge, 1936; Karadaglis *et al.*, 2003; Le Minor, 1999; Song *et al.*, 2013). There were, however, cases where symptoms associated with the absence of the sesamoid in question were felt

by the patient. The complete absence of both sesamoids was always accompanied by a relatively severe halluxal deformation, be it hallux valgus (HV) or hallux varus (Alshryda *et al.*, 2012; Lui *et al.*, 2013; Mason *et al.*, 2012; Wright, 1998). The most common symptom from a HS absence was localised pain directly plantar to the metatarsophalangeal joint (MTPJ) (Berquist, 2010; Jeng *et al.*, 1998; Kanatli *et al.*, 2006; Shtofmakher *et al.*, 2014; Williams *et al.*, 2009b; Yildirim *et al.*, 2006). In addition to the pain, the patient may have had HV or other deformities of the hallux (Alshryda *et al.*, 2012; Goez *et al.*, 1995; Lui *et al.*, 2013; Mason *et al.*, 2012; Wright, 1998; Yildirim *et al.*, 2006; Zinsmeister *et al.*, 1985). The absence of the MS was theorised to be a predisposing factor to HV, as the medial collateral ligament was either absent or underdeveloped and weak and, as such was said to no longer prevent the subluxation of the HS laterally (Mason *et al.*, 2012). Alternatively, in MS absence, the mechanism has been described as the inability for the medial head of the flexor hallucis brevis muscle (FHB) to stabilise the hallux, leading to an advantage of adduction forces with the lateral head of the FHB, in turn leading to HV deformity (Zinsmeister *et al.*, 1985). Absence of HSs may also mean an absence of the intersesamoid ridge and, as such, would be “a first real indication of an actual, developmentally based conditional cause for this widespread disease of the foot.” i.e., HV (Brenner *et al.*, 2002), inferring that HS absence pre-disposes an individual to HV in the affected foot.

Theories regarding the symptoms caused by HS absence have been generally based around abnormal kinematics. The loss of the HS was said to

cause an imbalance or loss of normal cushioning especially in MS absence, leading to focal pain or bursitis (Kanatli *et al.*, 2006; Williams *et al.*, 2009b). A bilateral absence of the MS with no sesamoidal tissue and normal appearing intersesamoid crista was reported (Young *et al.*, 2020). Interestingly, the tendons of the medial head of the muscle were observed to cross laterally and blend into the tendons of the lateral head in both feet, attaching into the lateral sesamoid (LS). This unusual anatomy was speculated to be a compensatory mechanism to achieve normal foot kinematics, that may explain why the patient did not suffer any symptoms or deformity relating to the hallux (Young *et al.*, 2020).

The reported incidence of HS absence varies greatly. Absence of the MS (0.25%) and the LS (0.08%) has been reported (Karadaglis *et al.*, 2003). This very low incidence of absence was based on a large 1032 sample population. Elsewhere, 35 feet were identified to have an absence of any HS out of 28 individuals, with 15 individuals (53.5% of total cases) showing bilateral involvement in some form. Within the reported 35 feet identified to have a HS absence, 12 feet (34.3%) were missing both sesamoids within the same foot, 17 feet (48.6%) were missing the MS alone, and 6 feet (17.1%) were missing the LS alone. HS absence tends to be bilateral or have a contralateral effect in the form of an underdeveloped or partite sesamoid. This suggests a link between absence of a HS and partism, which is a much more commonly identified HS abnormality at around 12% of the observed population (Yammine, 2015). Partism of the HS also has a high rate of bilateral presence, with a pooled prevalence estimate of 42.1%. Additionally,

the MS was affected in 10.7% of the population as opposed to 1.3% for the LS, and that those with HV were three times more likely to have a partite MS (Yammine, 2015). When comparing the metadata analysis of partism with the limited data gathered for the current study, there are similarities such as the propensity for MS absence, as well as higher incidence of HV and bilateralism. From these similarities, a link between HS absence and partism can be inferred, suggesting that partism is a less severe form of the mechanisms that lead to absence, be it from developmental sources as in types 1 or 2, or from an early injury or vascular insult as in types 2 or 3.

Partism has been identified to have a genetic link, with a far lower occurrence rate in middle eastern populations (Yammine, 2015). This genetic link could be used to further inform the basis of HS absence. Identifying a similarly low occurrence of HS absence in middle eastern populations would support the theory. The data available in the current review was severely limited, making further judgments unreliable.

The blood supply of the HS has also been investigated. The MS and LS had single nutrient arteries in 63% and 58% of cases, respectively (Pretterklieber, 1990) which was confirmed by others (Chamberland *et al.*, 1993). Other studies are reported opposing data, where the MS and LS had two to three nutrient arteries most of the time (Rath *et al.*, 2009; Sobel *et al.*, 1992). There was evidence, however, that of the nutrient arteries reaching a given HS, the most proximal nutrient artery tended to have a longer intraosseous path and was the main supply to the HS, alongside a

sometimes limited collateral supply (Chamberland *et al.*, 1993; Rath *et al.*, 2009; Sobel *et al.*, 1992). All of the current literature regarding the blood supply to the sesamoids was based on western populations. A comparison with other populations could confirm the link to partism, absence and blood supply (Sobel *et al.*, 1992).

The current study was limited by the rarity of the reports and the lack of pertinent information in some studies (Zhang *et al.*, 2020). However, the frequency of HS absence reporting is increasing. This is due to the increase in the availability of higher quality and more diverse imaging modalities for routine observation. This, and retrospective studies of large series of these scans, could reveal the true cost of HS absence, in terms of pain for patients and burden to healthcare systems. Further information may provide a clearer link between HS absence and aetiology of related foot disorders, and may help understand the mechanisms for both.

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Part 2

Detailed Interactions with the Hallucal Sesamoids

Part Two, Chapter One

2.1 Attachments of the Adductor Hallucis Heads onto the Lateral Hallucal Sesamoid

2.1.1 Introduction

Hallux valgus (HV), or bunion formation, is an extremely common foot deformity that affects 30-38% of women and 13-21% of men (Nix *et al.*, 2010; Roddy *et al.*, 2008). It is characterised by a destabilisation of the first metatarsal as a result of abnormal biomechanics, genetic pre-disposition and variant anatomy, or most commonly a tight toe box (Coughlin, 1996; Hannan *et al.*, 2013; Linder *et al.*, 1998; Mancuso *et al.*, 2003; Menz *et al.*, 2021; Nix *et al.*, 2012). This leads to a medial deviation of the first metatarsal bone alongside a lateral deviation of the first ray phalanges, including a progressive subluxation of the first metatarsophalangeal joint (MTPJ) (Coughlin *et al.*, 2013; Joseph *et al.*, 2007). These deformations of the hallux are a cause of pain, to the point of disability, and are equally of cosmetic concern (Coughlin *et al.*, 2013; Joseph *et al.*, 2007). Along with these problems, the deformity is associated with poor balance, immobility and an increased risk of falling (Benvenuti *et al.*, 1995; Menz *et al.*, 2001; Nilsdotter *et al.*, 2018). Conservative treatments of HV range from physical therapy, taping, padding and splinting, to modified shoes, manual manipulation therapy, and orthoses (Coughlin *et al.*, 2013; Du Plessis *et al.*, 2011; Easley *et al.*, 2007; Gur *et al.*, 2017). These conservative options have been shown to have mixed success, with the best functional results found after surgical intervention (Easley *et al.*, 2007; Torkki *et al.*, 2001). There are many

different types of HV correction surgery, with as many as one hundred different procedures described (Coughlin *et al.*, 2013; Easley *et al.*, 2007; Smyth *et al.*, 2018). However, there is one procedure that is recommended for nearly all cases, either alone, or in conjunction with other procedures: distal soft tissue release (Coughlin *et al.*, 2013; Schneider, 2013; Smyth *et al.*, 2018). This procedure utilises an approach into the first web space to release lateral structures contracted through the development of HV. Early authors stated that the cause of HV was the contracture of the conjoined tendons of the adductor hallucis (AdH) muscle heads and the flexor hallucis brevis (FHB) muscle attaching into the proximal phalanx (PPh) (McBride, 1928; Silver, 1923). Release of these muscles aims to correct the imbalance created by the deforming forces they produce (Coughlin *et al.*, 2013; Mann, 1990; McBride, 1928). As a result of this belief, the main targeted lateral structures are the AdH muscle tendons and the lateral joint capsule of the first MTPJ, as well as the deep transverse metatarsal ligament (DTMTL) (Coughlin *et al.*, 2013; Mann, 1990; Schneider, 2013; Wulker, 2000). This principle of balancing the structures around the MTPJ also applies to traumatic HV, such as in conditions like turf toe, where medial stabilising structures are traumatically damaged, and so the “imbalance” needs to be rectified using the same or similar surgeries (McCormick *et al.*, 2009, 2010).

In fact McGlamry’s surgical textbook states that “the adductor tendon is the first of the deforming structures to be evaluated and released” for HV correction surgery (Southerland *et al.*, 2012). This is echoed in other surgical textbooks (Coughlin *et al.*, 2013; Pfeffer *et al.*, 2017). Adequate exposure

and an understanding of the anatomy of the distal attachments of the AdH muscle heads should be vital in their safe targeting during this lateral soft tissue release (Sammarco, 2008; Southerland *et al.*, 2012; Valvo *et al.*, 1987). However, their direct distal attachments to the lateral sesamoid (LS) and/or the PPh are not clearly defined, nor are indirect attachments; in these cases, fibrous structures from numerous sources may converge to attach distally via a common structures; sectioning of such a common structure may have broader functional implications than appreciated or predicted (Hawkins, 1971; Miller, 1975; Owens *et al.*, 2001). Little consideration is also given to structures that may course through the area of sectioning, with more distal targets (Lin *et al.*, 1996).

The distal attachments of the AdH have previously been investigated finding that the oblique head (OH) had one to three components (Arakawa *et al.*, 2003; Frohse, 1913; Kelikian *et al.*, 2011; Valvo *et al.*, 1987) and that the transverse head (TH) had one or three components (Arakawa *et al.*, 2003; Cralley *et al.*, 1979; Kura *et al.*, 1997). The descriptions of the OH and TH distal attachments vary between the LS, the plantar aspect of the LS or the proximal phalanx, specifically with the OH attaching to the LS and the TH attaching to either the OH or to both the LS and proximal phalanx (Kelikian *et al.*, 2011; Lin *et al.*, 1996; Owens *et al.*, 2001; Schneider, 2012; Valvo *et al.*, 1987; Wulker, 2000). Some additional details have been observed such as the TH attaching onto the extensor aponeurosis or terminating on the flexor hallucis longus (FHL) tunnel (Leboucq, 1893; Valvo *et al.*, 1987).

The precise distal attachment of the AdH muscle was ambiguous in the reviewed literature, highlighted by the lack of consensus on the subdivisions of the muscle heads. Most suggested exclusive attachment to the proximal phalanx (Coughlin, 1996) as primarily represented diagrammatically (Austin *et al.*, 1981; Coughlin, 1996; Joplin, 1950; Mann, 1986; McBride, 1928; Miller, 1975; Resch *et al.*, 1989; Schneider, 2012). Most surgical texts simplify the distal attachments of the TH and OH to describe a conjoined AdH tendon attaching to the LS and the PPh (Kelikian *et al.*, 2011; Lin *et al.*, 1996; Owens *et al.*, 2001; Schneider, 2012; Southerland *et al.*, 2012; Wulker, 2000). This conjoined AdH tendon is a target in most distal soft tissue release techniques, so it is vital to understand what constitutes the conjoined tendon and what other structures are at risk. However, there are no described distinctions for other neighbouring attachments to the proximal phalanx or LS (Lin *et al.*, 1996; Mann, 1990; Southerland *et al.*, 2012).

The lack of direct anatomical confirmation during a distal soft tissue release results in a large percentage (25-50%) of cases where the intended structures were not adequately sectioned, putting neighbouring structures at risk (Lin *et al.*, 1996; Owens *et al.*, 2001). This unpredictability could lead to unwanted outcomes from releasing other lateral tissues such as the lateral tendon of the FHB muscle, the sesamophalangeal ligament, or even damaging the articular cartilage on the first metatarsal head (Hawkins, 1971; Joplin, 1950; Lin *et al.*, 1996; Owens *et al.*, 2001). The FHB is especially at

risk when carrying out adductor tenotomies, as the lateral head of the FHB is described as being difficult to differentiate from the medial parts of the OH (Owens *et al.*, 2001). There is also the chance that the structures providing the deforming forces that contribute to HV progression are left intact, with no advantage to the patient postoperatively (Lin *et al.*, 1996).

It is clear that the course, attachments and relations of the AdH muscle in proximity to the first ray are poorly understood. This study aims to map these in order to provide accurate information that may inform more effective distal soft tissue release for the treatment of HV.

2.1.2 Materials and Methods

Feet from embalmed (Genelyn Anatomical Series, Australia; see Appendix 5.1) Body Donors (n = 40; female = 23, male = 17; mean age = 84.2 $\pm$ 4.2 years) were examined in accordance with *Part IV of the Human Tissue Act (1992)* and with local ethics approval (project ID: 12292). Exclusion criteria included any signs of previous surgery, and specifically, anything directly related to adductor release procedures, such as visual hallux valgus, or hallux varus.

Skin was incised along the 2nd web space and reflected to reveal the underlying fascia encasing the deeper tissues of the first and second rays. On the plantar aspect of the foot, the AdH heads were identified laterally. A fascicular dissection strategy (see Appendix 5.2) was employed to follow along the plantar surface of each muscle belly towards the first ray. Fascicular dissection involves the direct observation of individual tissue fascicles under magnification. Decision-making regard tissue retention or removal was based on the course of specific fascicles for all muscle, tendon, ligament, and capsular tissues. A surgical microscope (Wild Heerbrugg M651, Switzerland) was used to observe these tissues under 7-36x magnification, as required. Tissues were dissected until fascicles termination, either in skeletal attachment, or by converging with other soft tissues.

Soft tissue structures were digitally photographed (EOS5D mark III, Canon, Japan). Once clear visualisation of the tissues had been recorded

those tissues attaching to bone were cut down to their attachment, leaving a short stump on the bone. These “footprints” of attachment were then modelled into a virtual 3D space using a digital microscribe (MicoScribe G2X, ImmersionCorp, USA; see Appendix 5.3). The microscribe records the 3D coordinates of a single point into a virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA). A sequence of points located along a surface were converted into a digital line, and a series of digital lines used to render a model of a surface in the virtual environment (Figure 2.1.1). Utilising this process for each footprint not only rendered them in 3D, but allowed measurements of each to be taken, inclusive of their curvature. Footprints were modelled in triplicate to facilitate assessment of the accuracy and reproducibility of the process. Images were reviewed with an expert team including anatomists and clinicians, but measurements done in triplicate were done by the author as a single intra-observer study. The area and perimeter of each footprint was measured in the virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA).

The small size and close relations of the skeletal surfaces in the area of concern (LS, metatarsal head, PPh) limited the ability to accurately model them with a microscribe. More detailed models were generated using micro-CT (SkyScan, Bruker, Kontich, Belgium; see Appendices 5.4 and 5.5). Segmentation of the bone from these scans enabled 3D models of the skeletal elements to be generated; these were combined with the microscribe data to produce accurate 3D maps of the attachments to these elements.

To aid 3D visualisation of data, surface scans of relevant skeletal surfaces were created using a laser surface scanner (Artec3D, Luxembourg; see Appendices 5.6-5.9).

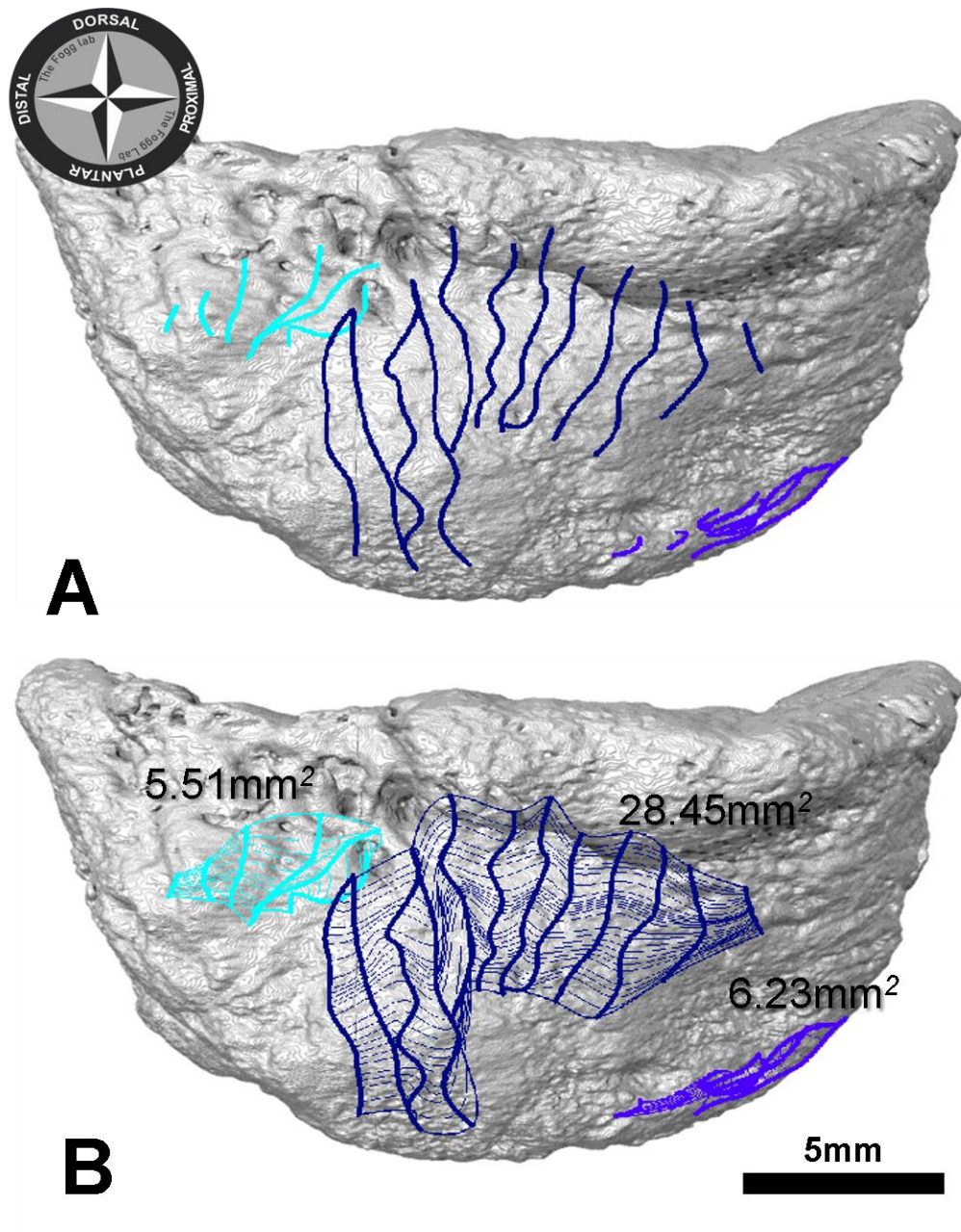


Figure 2.1.1. Adductor hallucis attachments demonstrated on a micro CT model of a lateral sesamoid overlaid with 3D attachment footprints generated with a digital microscribe. **A** –Lateral view of a lateral sesamoid demonstrating the curves taken with the microscribe from three separate adductor hallucis footprints. The medial oblique head component (deep blue), the lateral oblique head component (purple) and the mixed oblique and transverse head slip into a fovea (cyan) **B** – Lateral view the lateral sesamoid demonstrating lofted lines which created a measurable 3D surface.

2.1.3 Results

The TH of the AdH muscle was found to be attached to the LS (mean attachment area = $6.7 \pm 2.4 \text{ mm}^2$) (Figures 2.1.1 and 2.1.2). These fibres interdigitated onto the OH tendon at and within 10mm of the level of the proximal pole of the LS. Interdigitations between the TH and OH tendon fibres were variable occasionally with muscular fibres (Figure 2.1.3A) and/or tendinous fibres (Figure 2.1.3B). In several specimens (n=10; 25%), there was a distinct band of fibres from the TH that joined a set of fibres from the OH (Figure 2.1.1 and 2.1.2). This coalescence formed a distinct attachment either onto the central portion of the LS (n=6; 15%), onto the edge of the collateral ligament (n=5; 12.5%), or, less commonly, into a clear fovea (n=2; 5%) (Figure 2.1.1). These fibres ran over the dorsal aspect of the longitudinally running fibres of the OH and attached to the LS in an oblique direction. The TH therefore had no wholly independent attachments to the LS, as even within the distinct band, there was an interdigitation with OH fibres. An abnormal attachment was identified (n=1, 2.5%) where the antero-lateral fibres of the TH ran superficially to the OH and TH interdigitations and fanned out at the level of the LS to communicate with the extensor aponeurosis and the PPh (Figure 2.1.4)

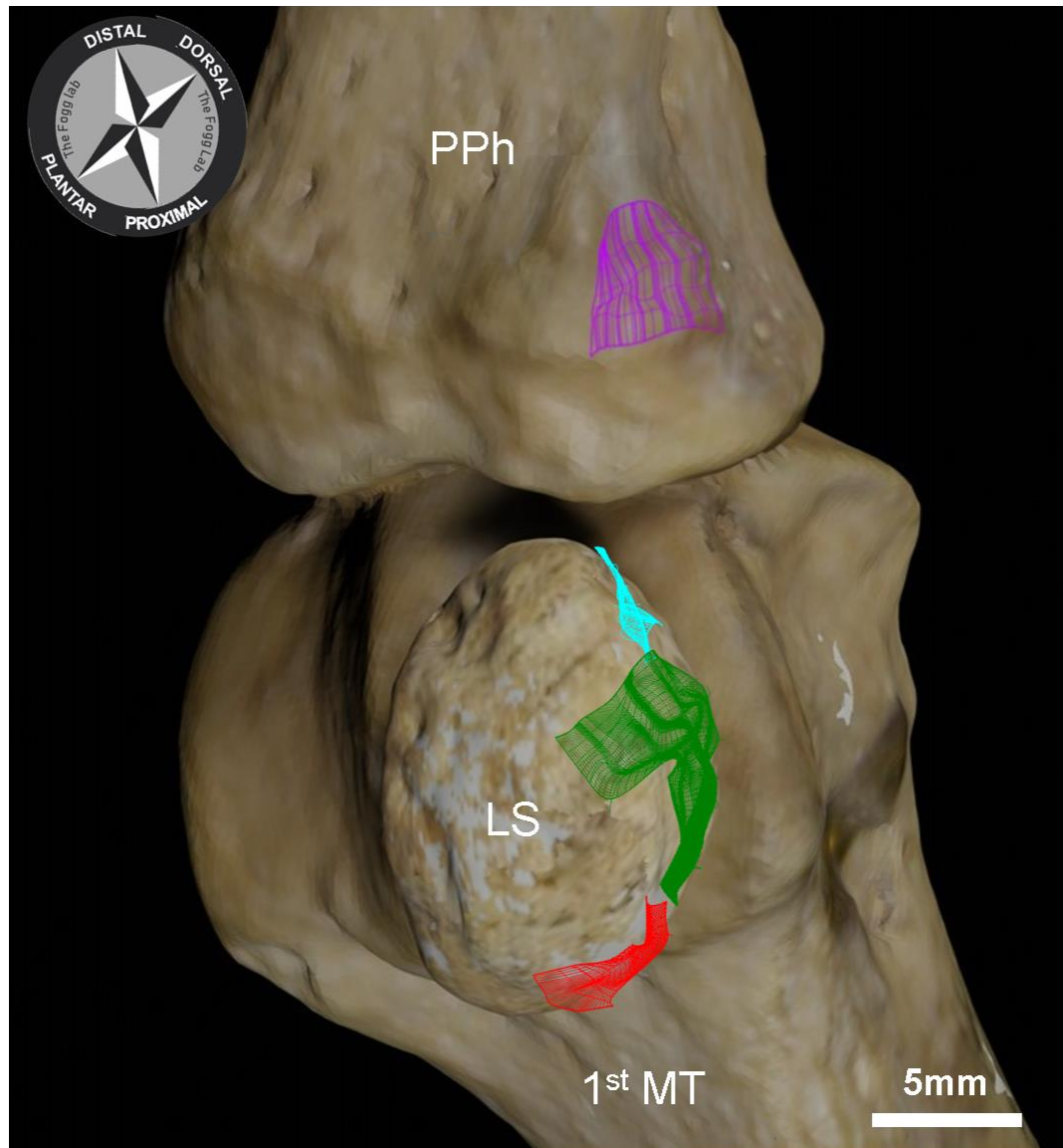


Figure 2.1.2. A plantar lateral view of a 3D model made from Artec texture scanning, micro-CT scans and microscribe data. Highlighting the footprints of the adductor hallucis, on the lateral sesamoid (LS): with the proximal oblique head separate attachment (red footprint), the main oblique head footprint (green footprint), and the transverse and oblique head distinct attachment (cyan footprint). On the proximal phalanx (PPh) the distal footprint of the adductor hallucis (purple footprint) on the plantar lateral aspect of the plantar lateral tubercle.

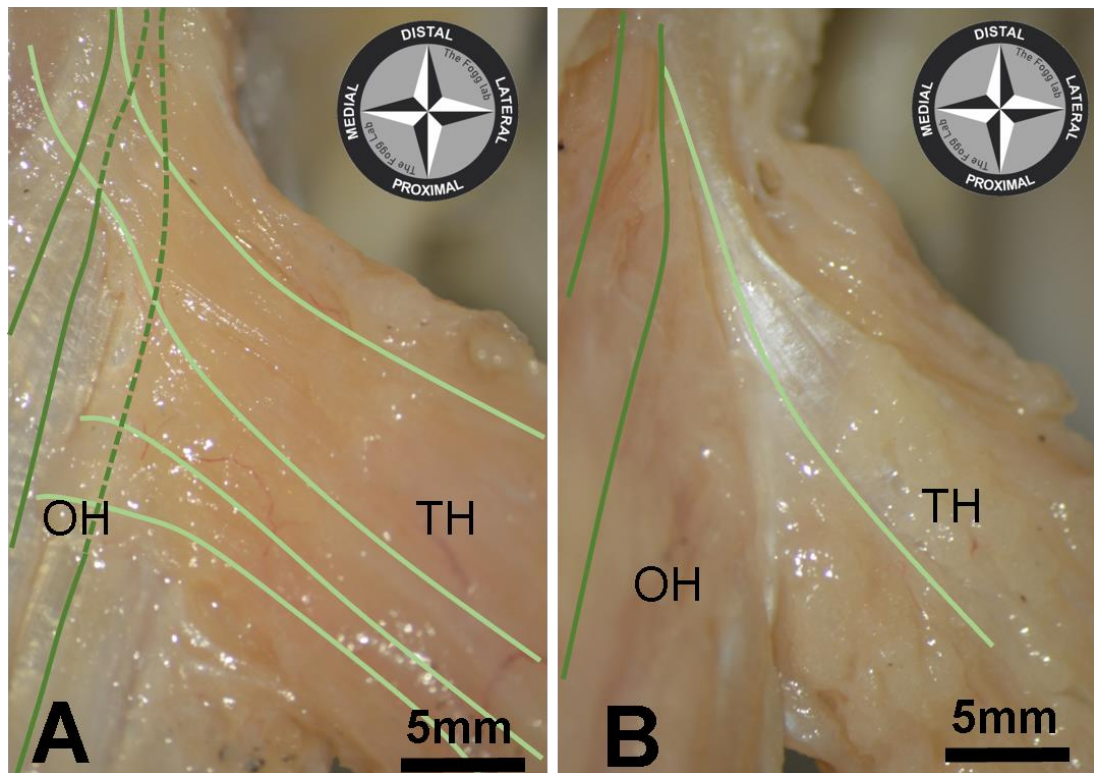


Figure 2.1.3. The tendinous and muscular attachments between the transverse head (TH, light green lines) and the oblique head (OH, dark green lines) of the adductor hallucis muscle. A – dorsal view demonstrating the TH muscular fibres attaching to the tendon of the OH. B - Dorsal view demonstrating the TH tendon interdigitating with the tendon of the OH.

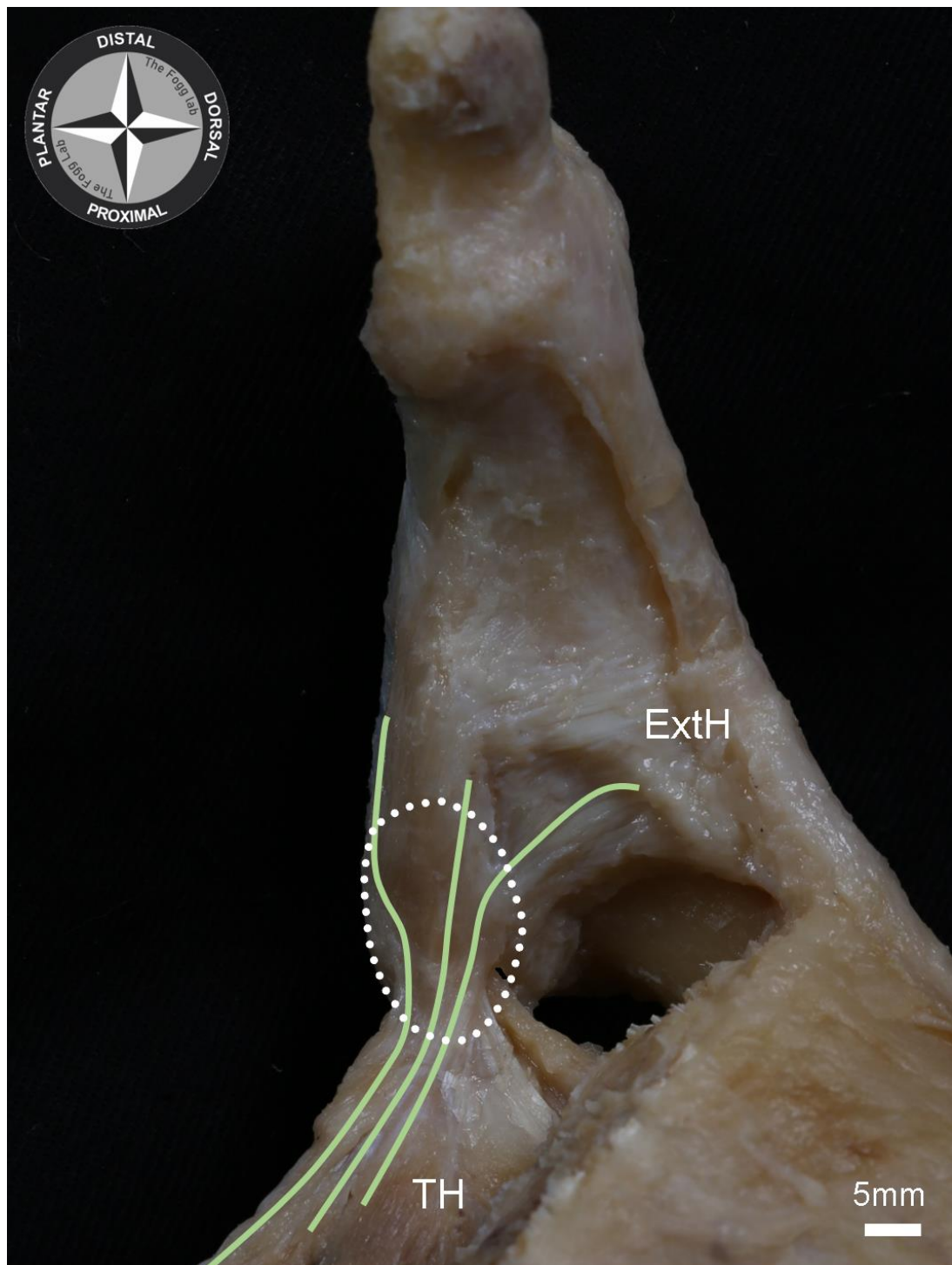


Figure 2.1.4. Dorsolateral view of a dissection of the hallux, with the lesser toes removed. Highlighting the course of the anterior-most fibres (light green lines) of the transverse head (TH) fanning out at the level of the lateral sesamoid (white dotted line) to merge into superficial tissues of the proximal phalanx and extensor hood (ExtH).

The OH of the AdH muscle had a significantly larger mean attachment ($25.6 \pm 6.9 \text{ mm}^2$; $p < 0.05$) to the LS than the TH. It attached, in parts, to the proximal pole and the lateral surface of the LS (Figures 2.1.1 and 2.1.2). Occasionally, the footprint split ($n=2$; 5%), with the more superficial fibres reaching a small attachment proximal on the LS and the main body of fibres attaching along a broader more lateral aspect of the LS (Figures 2.1.1 and 2.1.2). Beyond the LS, the superficial OH fibres blended medially with the lateral sesamophalangeal ligament, forming a tendino-ligamentous complex (Figure 2.1.5). This complex included some fibres from the TH, as well as fibres from the lateral tendon of the FHB muscle.

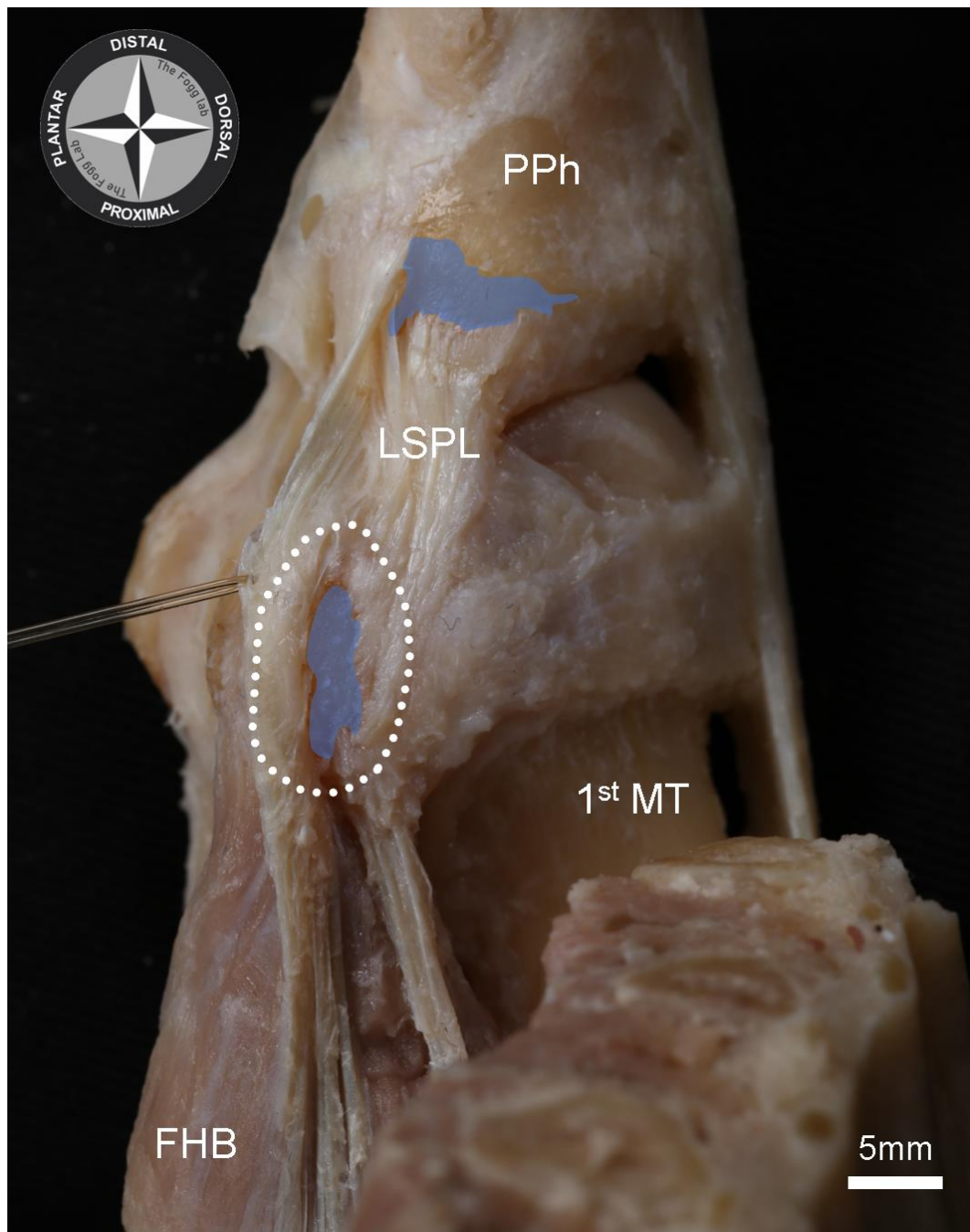


Figure 2.1.5. A Lateral view of the first metatarsophalangeal joint dissected to reveal the footprints of the adductor hallucis. Onto the lateral sesamoid (white dotted line) as shown with the proximal blue shadow, and the distal footprint onto the proximal phalanx (PPh) highlighted by the distal blue shadow. The underlying lateral sesamophalangeal ligament (LSPL) is made visible by the removal of the adductor hallucis fibres. FHB: Flexor hallucis brevis; 1st MT: First metatarsal.

The “conjoined” tendon of both AdH heads was identified to have a superficial group of fibres that did not attach directly to the LS but continued distally to attach onto the plantar lateral tubercle of the PPh, with a mean footprint of $37.2 \pm 9.5 \text{ mm}^2$ (Figures 2.1.2 and 2.1.5). Past the LS these fibres were contiguous to the deeper sesamophalangeal ligament (Figure 2.1.5)

The AdH was consistently interdigitated with by the lateral head of the FHB (n=40, 100%), with a direct tendon interdigitation just proximal to the LS proximal pole (Figure 2.1.6), as well as muscular connections further proximally along the medial part of the OH.

In summary the TH was consistently attached to the LS, via interdigitations with the OH tendon or muscle with an occasional distinct attachment site onto the LS with distinct fibres from the OH. The TH had no entirely independent attachment to the LS, but did on occasion communicate with the extensor aponeurosis. Both the TH and OH had superficial components that were found to attach distally to the PPh, overlying their deeper counterparts and the lateral sesamophalangeal ligament. The AdH was consistently seen to be contributed to by the lateral head of the FHB.

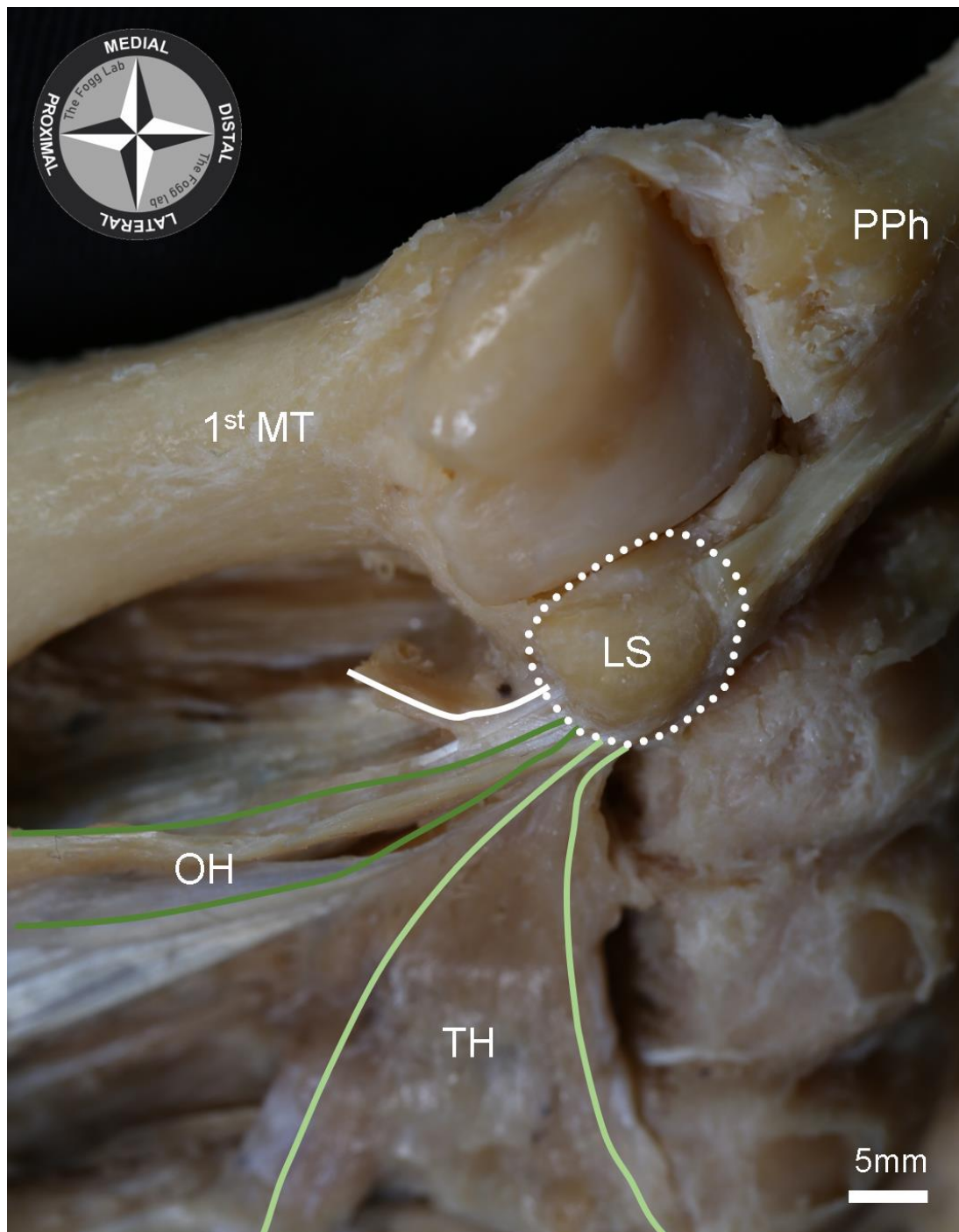


Figure 2.1.6. A plantar medial view of a dissection of the plantar hallux, with the medial sesamoid removed leaving the lateral sesamoid (LS, white dotted line), highlighting the strong attachments of the transverse head (light green lines) and oblique head (dark green lines) of the adductor hallucis to the proximolateral aspect of the lateral sesamoid. As well as the merging tendinous portion of the lateral head of the flexor hallucis brevis (white line) into the oblique head fibres. PPh: proximal phalanx.

A bursa was identified (n=3;7.5%) between the lateral side of the AdH tendons and the tendon of the first dorsal interosseous muscle at the level of the LS (Figure 2.1.7). Occupying the first webspace between the metatarsal heads, this bursa was thin-walled and extremely delicate. In one specimen (2.5%) an identifiable fluid connection was seen from the bursa towards the adjacent second MTPJ capsule.

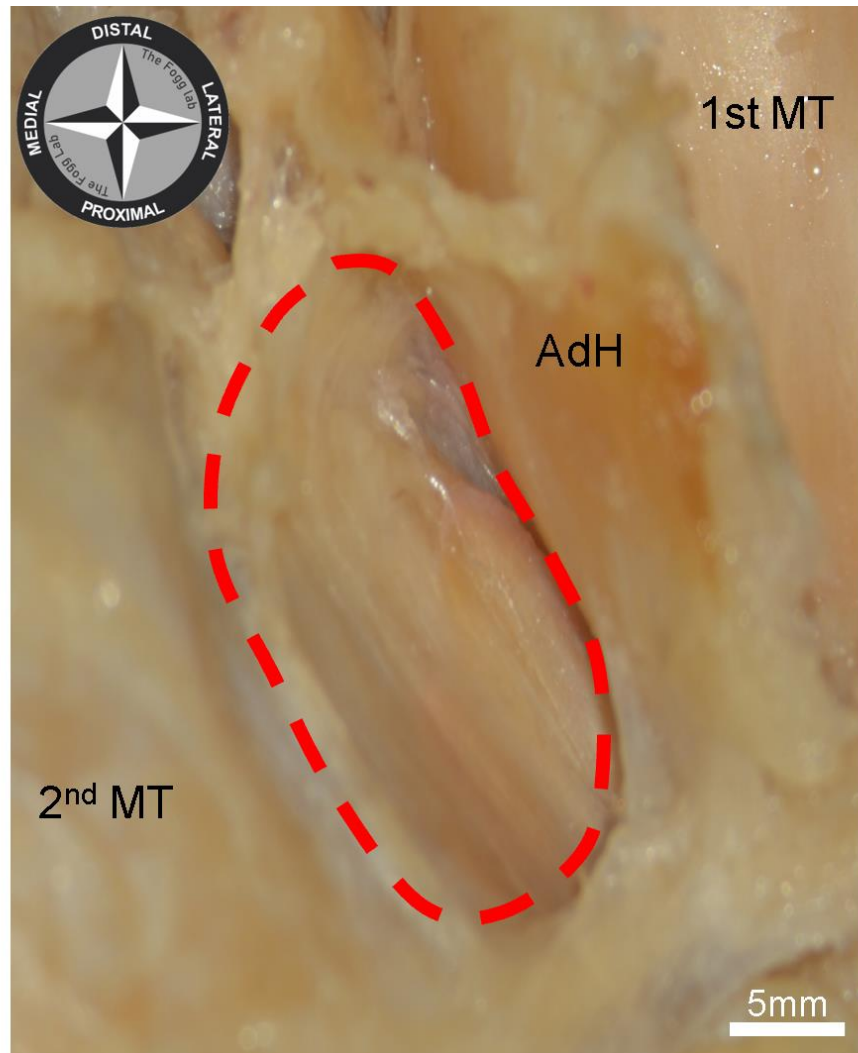


Figure 2.1.7. A dorsal view of a bursa (red dash) between the attachments and tendons of the adductor hallucis (AdH) and the 2nd metatarsal head (2nd MT). 1st MT: first metatarsal.

2.1.4 Discussion

Understanding exactly where the adductor hallucis muscle heads attach, and therefore exert their pull, may improve tissue selection in distal soft tissue releases for HV (Lin *et al.*, 1996; Sammarco *et al.*, 2001; Sammarco, 2008). The current study demonstrated that the AdH muscle has distinct attachments to the LS bone. The deep fibres of the OH always attached onto the lateral surface of the LS, sometimes with split footprints. The most superficial fibres of the OH continued distally to the PPh, along with some TH fibres, the lateral sesamophalangeal ligament and the lateral tendon of the FHB muscle, as previously described (Miller, 1975; Schneider, 2012, 2013). Others, however, suggested that OH attachments were limited to the LS and the first MTPJ, and those of the TH to the LS, the first MTPJ and the lateral surface of the PPh (Arakawa *et al.*, 2003). The current findings do not support this suggestion, as the superficial fibres from the OH could be followed over the LS to the PPh, whereas the fibres from the TH were too interdigitated with those of the OH to be specifically traced to the PPh. The difference in results may be due to differences in methodology, but a clear account was not provided in the former work, making direct comparison impossible.

These data suggest that the OH is the main muscle attachment to the LS, which confirms previous suggestions that most of the OH attached to the lateral and plantar aspects of the LS (Arakawa *et al.*, 2003; Kelikian *et al.*, 2011; Valvo *et al.*, 1987). Previous literature found that the OH was made up

of either two (Arakawa *et al.*, 2003; Martin, 1964) or three components (Kelikian *et al.*, 2011; Valvo *et al.*, 1987), as did the current study. However, it cannot be confirmed that the split footprints came from different components of the OH. In the current study, it was recognised that the OH did indeed interdigitate with the TH just proximal to the LS (Cralley *et al.*, 1979; Kelikian *et al.*, 2011; Owens *et al.*, 2001; Valvo *et al.*, 1987). Only one instance of an identifiable localised slip from the TH attaching to the lateral border of the LS had been identified within the literature (Cralley *et al.*, 1979). In the current study, this was observed attaching into the bony surface fovea (Figure 2.1.1). This distinct slip was, however, interdigitated with an OH tendinous components before reaching the fovea.

Previous work identified the TH to be absent in 6-9% of their specimens (Cralley *et al.*, 1979; Kura *et al.*, 1997). The findings of the current work identified the TH in all specimens. One of the previous methodologies included a de-fatting step which may have dissolved away any fat infiltrated transverse heads, a relatively common observation among more elderly Body Donors, alongside the theory that the TH is less developed and more degenerative than the OH (Arakawa *et al.*, 2003; Cralley *et al.*, 1979).

Differentiating between the lateral head of the FHB and the medial part of the OH has been a matter of concern for authors trying to isolate the OH for soft tissue release (Owens *et al.*, 2001). The FHB can be iatrogenically damaged as a result (Lin *et al.*, 1996). This research identified

consistent and accurate FHB contributions to the OH in the form of tendinous and muscular inputs (Figure 2.1.3). This was achieved by means of fascicular dissection which allowed for clear visualisation of connections. These results confirm the inextricable connection between the two muscles.

A bursa was identified in the first webspace between the first and second metatarsal heads. Very little reference is made to the bursa in the literature (Bossley *et al.*, 1980; Zanetti *et al.*, 1997) even though the first webspace bursa is considered the largest of the intermetatarsal bursae (Zanetti *et al.*, 1997). It has been proposed that this intermetatarsal bursa is involved in a range of pathologies, such as Morton's metatarsalgia, intermetatarsal bursitis and Morton's neuroma (Awerbuch *et al.*, 1982; Bossley *et al.*, 1980; Chauveaux *et al.*, 1987; Linklater, 2012; Zanetti *et al.*, 1997). In the current study, a single specimen had a fibrous connection from the bursa towards the adjacent MTPJ capsule. This bridging of the bursae toward neighbouring MTPJs has been previously reported (Awerbuch *et al.*, 1982; Bossley *et al.*, 1980), and has been reported to arthritic changes from neighbouring diseased MTPJs (Awerbuch *et al.*, 1982). It was previously suggested that the bursa could not be reliably dissected after an interval of 72 hours after death, due to the extreme fragility of the tissue (Chauveaux *et al.*, 1987). This fragility may explain why so few were readily observed in this series, or in previous studies. Future dissections in this space would benefit from a more purposeful approach to the intermetatarsal area, by stabilising the bursae with an injectable, and contrast enhancing it for more accurate imaging studies. This would highlight the possible connections between the

bursa and the adjacent MTPJs, clarifying any link between these bursae and conditions of the MTPJs.

Reviewed descriptions of surgical techniques for the release of the AdH tendons lacked precise, clear and reproducible information, both in the research literature (Austin *et al.*, 1981; Coughlin, 1996; Lin *et al.*, 1996; Okuda *et al.*, 2000; Petratos *et al.*, 2008; Resch *et al.*, 1989) and in surgical texts (Kelikian *et al.*, 2011; Southerland *et al.*, 2012). Combined with imprecise anatomical data, the lack of specific detail may limit the ability to target specific structures, or obfuscate the need for such specificity. For an AdH tenotomy, the current literature suggests a dorsal approach into the first webspace. The principle aim, as reported, is to: *seek out the AdH conjoined tendon at its point of attachment to PPh, clamp it at the level of the first MTPJ and “sharply” release it from the PPh. The AdH conjoined tendon is then dissected proximally to strip it from the LS, and release any other attachments the AdH may have in the intermetatarsal space* (Southerland *et al.*, 2012). This description makes the potentially dangerous assumption that the AdH is the only structure that could be incised during its “sharp” release from the PPh (Lin *et al.*, 1996). The potential damage to untargeted structures when making an indiscriminate incision into this tendino-ligamentous complex could have biomechanical repercussions and negative clinical outcomes. Outcomes such as recurrence, transfer metatarsalgia, non-union, avascular necrosis but most common, hallux varus (Easley *et al.*, 2007; Hawkins, 1971; Leemrijse *et al.*, 2008; Lin *et al.*, 1996; Miller, 1975; Plovanich *et al.*, 2012; Sammarco *et al.*, 2001; Thompson, 1990).

Hallux varus has been stated as most often being an iatrogenic complication of HV (Plovanich *et al.*, 2012). It is estimated that the post-operative occurrence of hallux varus ranges from 2-15.4% (Leemrijse *et al.*, 2008). Considering the high volume of HV surgery performed, this leaves many post-operative patients dissatisfied, still in pain, and unable to wear selected footwear (Sammarco *et al.*, 2001). The reported causes for iatrogenic hallux varus are excessive soft tissue release, with release of the conjoined tendons of both AdH heads and the lateral head of FHB tendon (Miller, 1975), or LS excision (Plovanich *et al.*, 2012). The mechanics of the hallux varus deformity start with the release at the lateral aspect of the MTPJ and LS leaving the medial deforming forces unopposed, leading to an “imbalance”, pulling the hallux into varus (Leemrijse *et al.*, 2008; Turner, 1986). Hallux varus is often treated with medial soft tissue releases, lateral soft tissue repairs and AdH tendon transfers (Hawkins, 1971; Leemrijse *et al.*, 2008; Miller, 1975). Thus, many of the surgeries either for hallux varus, and as seen for HV, aim to correct an “imbalance”, that can ultimately create further imbalances or MTPJ instability. With a map of the attachment sites of the AdH on the LS, the tendons of both heads can more accurately be targeted for release, for more consistent surgical outcomes, potentially minimising postoperative, iatrogenic imbalances.

There is contention about the necessity of releasing the AdH at all (Resch *et al.*, 1994; Schneider, 2012, 2013). Adductor tenotomy has been reported to improve the HV angle by only 2.3 degrees and did not improve satisfaction scores when combined with an osteotomy (Resch *et al.*, 1994).

More recent research found that HV can be corrected whilst avoiding distal soft tissue releases, finding positive outcomes (Klemola *et al.*, 2014). It has also been reported that complete release of the AdH tendons from both the PPh and the LS was never achieved, with a 100% failure rate (Lin *et al.*, 1996). If the targeted structures aren't being released on a regular basis, without quantifiable differences in surgical outcome, then how important is it to release the AH? Although there were no clear anatomic relations discussed in the literature from a surgical release perspective, similar applications have been discussed in relation to the thumb (Sato *et al.*, 2018, Jakubietz *et al.*, 2020). These studies suggest that a better understanding of soft tissue layering around a similarly important joint can inform improved clinical management.

The current study had a number of limitations. The detailed, multi-modal approach greatly extended the time required with each specimen, effectively limiting the sample population. The greater detail, and proven reproducibility of the data may be considered as foundations for future work. Within this study, only intra-observer variation was assessed, future studies can include interobserver observation on key findings. As determined in this investigation, the first webspace bursa requires specific preparation to be more thoroughly examined. Whilst embalmed Body Donors are excellent models for the detailed examination of static anatomy, the use of unembalmed Donors may facilitate the inclusion of additional data, such as stretch and strength of specific tissues. This may provide more information specific to the operative limitations encountered in this area. This study has demonstrated the specific attachments of the AdH muscle, confirming the

prominent involvement of the LS bone. The detailed 3D relations of its attachments may help refine distal soft tissue releases HV and promote further investigations into this complex anatomical area.

2.1.5 References

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Part Two, Chapter Two

2.2 Detailed Anatomy of the Deep Transverse Metatarsal Ligament

2.2.1 Introduction

Hallux valgus (HV) is an extremely common foot deformity (Nix *et al.*, 2010; Roddy *et al.*, 2008). Surgical repair is considered most effective (Easley *et al.*, 2007; Torkki *et al.*, 2001), with a large variety of procedures described to address diverse levels of deformity (Coughlin *et al.*, 2013). Soft tissue releases for HV most often target lateral structures, including the adductor hallucis tendons, the lateral joint capsule of the first metatarsophalangeal joint (MTPJ) and the deep transverse metatarsal ligament (DTMTL) (Coughlin *et al.*, 2013; Schneider, 2013).

During the development of HV, the first metatarsal (MT) is deviated medially, whereas the hallucal sesamoids remain in position. The lateral hallucal sesamoid is anchored by the DTMTL and the adductor hallucis tendons (Schneider, 2013). Both structures are also reported to attach to the proximo-lateral end of the proximal phalanx; in HV, these connections may contribute to proximo-lateral deforming forces acting upon the proximal phalanx, resulting in further medial displacement of the first metatarsal head (Schneider, 2013). Both the anchoring of the sesamoids and the deforming forces producing HV are why these structures are targeted during soft tissue releases. The release of these tissues may therefore reduce deforming forces on the proximal phalanx and allow the hallucal sesamoids to be

returned to their optimal position (Schneider, 2013). Accuracy of release may be important, as too little or too great a release may create biomechanical imbalance (Leemrijse *et al.*, 2008; Turner, 1986). There is further evidence that these soft tissue releases cause further first MTPJ instability and hallux varus, in part due to a lack of clear anatomy leading to inaccurate and potentially unnecessary sectioning (Kura *et al.*, 1998; Leemrijse *et al.*, 2008; Lin *et al.*, 1996; Schneider, 2013; Valvo *et al.*, 1987).

The deep transverse metatarsal ligament (DTMTL) is a key structure when considering HV repair. Failure to resect the DTMTL correctly is associated with avascular necrosis, overcorrection and instability (Schneider, 2013; Valvo *et al.*, 1987; Wang *et al.*, 2015). The DTMTL has been shown to be vital in maintaining distal intermetatarsal distance, conserving first MTPJ stability and anchoring the sesamoids (Abdalbary *et al.*, 2016; Kura *et al.*, 1998; Stainsby, 1997). Despite the clear importance of the DTMTL, its anatomy is yet to be clearly and consistently described. The DTMTL has been described as a fibrous connection between the lateral hallucal sesamoid and the plantar plate of the second MTPJ (Schneider, 2013). Some studies report two heads (Alvarez *et al.*, 1984; Valvo *et al.*, 1987), whereas most describe a single component (Barg *et al.*, 2012; Coughlin *et al.*, 2013; Schneider, 2013). The medial attachment was most commonly described as being plantar on the lateral aspect of the lateral sesamoid and the plantar plate; the lateral attachment was described onto the medial border of the second MTPJ plantar plate (Haines *et al.*, 1954; Kelikian *et al.*, 2011; Richardson, 1987; Valvo *et al.*, 1987). These descriptions did not convey the

course of the DTMTL, or its exact attachment sites, nor did they give a clear sense of the three-dimensional relations of the attachments. Such understanding is essential for accurate identification and release of the DTMTL and related tissues without unintended damage to neighbouring structures (Lin *et al.*, 1996).

Therefore, the aim of this study was to describe the DTMTL, including any subdivisions, and their attachments in three dimensions. This information could inform more precise soft tissue releases during HV surgery, improving functional outcomes and reducing complications.

2.2.2 Materials and Methods

Feet from embalmed (Genelyn Anatomical Series, Australia; see Appendix 5.1) Body Donors (n = 21; female = 12, male = 9; mean age = 82.1 $\pm$ 4.2 years) were examined in accordance with *Part IV of the Human Tissue Act (1992)* and with local ethics approval (project ID: 12292). The DTMTL is implicated in first ray deformities, therefore specimens were excluded from this study if on visual inspection there was any deformation of the first and second rays, any obvious hallux varus or hallux valgus and during the dissection process if any gout was identified within the MTPJ. Specimens were screened via in-lab x-ray (see Appendix 5.10) and CT imaging (see Appendix 5.11) for osteophytic growths within the joint, and excluded if signs of degeneration were identified..

Dorsal and plantar approaches onto the second MTPJ plantar plate (PP) and the lateral sesamoid were made. A fascicular dissection strategy (see Appendix 5.2) was employed to follow along the superficial surface of each structure. Fascicular dissection involved the direct observation of individual tissue fascicles under magnification. Decision-making regarding tissue retention or removal was based on the course of specific fascicles. A surgical microscope (Wild Heerbrugg M651, Switzerland) was used to observe these tissues under 7-36x magnification, as required. Tissues were dissected until fascicles terminated, either in skeletal attachment, or by converging with other soft tissues. During the dissection any structures spanning the space between the first and second MTPJs were noted and

photographed (EOS 5D mark III, Canon, Japan). Where a structure attached into bone, the “footprint” of the attachment was clearly delineated by the removal of any adjacent soft tissues, including periosteum. Where adjacent tissues included other attachments of note, ink was used to demarcate the boundary between attachment sites, based on the course of fascicular tissues.

Each footprint on the lateral sesamoid was outlined and modelled into a virtual 3D space using a digital microscribe (MicoScribe G2X, ImmersionCorp, USA; see Appendix 5.3). The microscribe recorded the 3D coordinates of a single point into a virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA). A sequence of points located along a surface was converted into a digital line, and a series of digital lines used to render a model of a surface in the virtual environment (Figure 2.2.1). Utilising this process for each footprint not only rendered them in 3D, but allowed measurements of each to be taken, inclusive of their curvature. Footprints were modelled in triplicate to facilitate assessment of the accuracy and reproducibility of the process, images were reviewed with an expert team including anatomists and clinicians, but measurements were carried out by the author as a single intra-observer study. The area and perimeter of each footprint was measured in the virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA). To facilitate this process over the entire surface of the sesamoid, footprints were dissected off once their modelling sequence was complete. This facilitated clear observation, modelling and measurement of subsequent footprints.

The digital models of each footprint were then matched to their respective CT data. These data had been segmented and meshed to create models of the lateral hallucal sesamoid. Overlying the sesamoid models with the corresponding footprint models allowed visualisation of the complete array of footprints on the lateral sesamoid bone in three dimensions.

To aid 3D visualisation of data, surface scans of relevant skeletal surfaces were created using a laser surface scanner (Artec3D, Luxembourg; see Appendices 5.6-5.9).

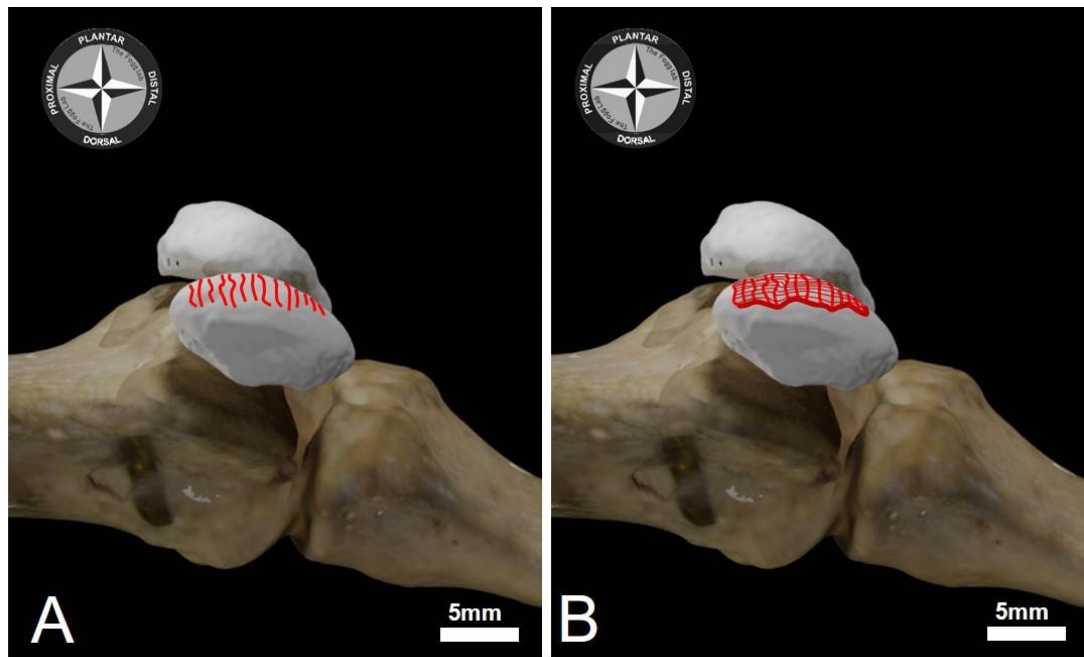


Figure 2.2.1. Microscribing the plantar DTMTL footprint onto the lateral sesamoid, a lateral view of the first MTPJ, with A. the lines microscribed directly onto the specimen. B - the lines lofted to create a measurable three dimensional surface The selected area was (red) was 34.94mm².

2.2.3 Results

The DTMTL was found to have two components (Figure 2.2.2; see Figure 4.4.1) in all specimens ($n = 21$; 100%), one dorsal component and one plantar component (Figure 2.2.2).

The more proximal third of the dorsal component of the DTMTL was found to be membranous and thin at around 0.01mm thick, whereas the more distal two-thirds were more substantial at a thickness of 0.45mm (17-195L, bulk with added measures from specimens). The plantar component of the DTMTL was consistently thicker than the dorsal component (Figure 2.2.3).

The dorsal component was attached laterally to the dorsal-medial aspect of the second MTPJ PP and medially to the capsule of the first MTPJ. The fibres of the dorsal component of the DTMTL ran dorsomedially and melded into the extensor aponeurosis and surrounding tissues that cover the dorsal aspect of the first MT head. The melding of the fibres meant that no observable footprint was identified, and thus could not be outlined and measured (Figure 2.2.4).

The plantar component of the DTMTL extended from the plantar aspect of the second MTPJ PP to the plantar-lateral aspect of the lateral sesamoid.

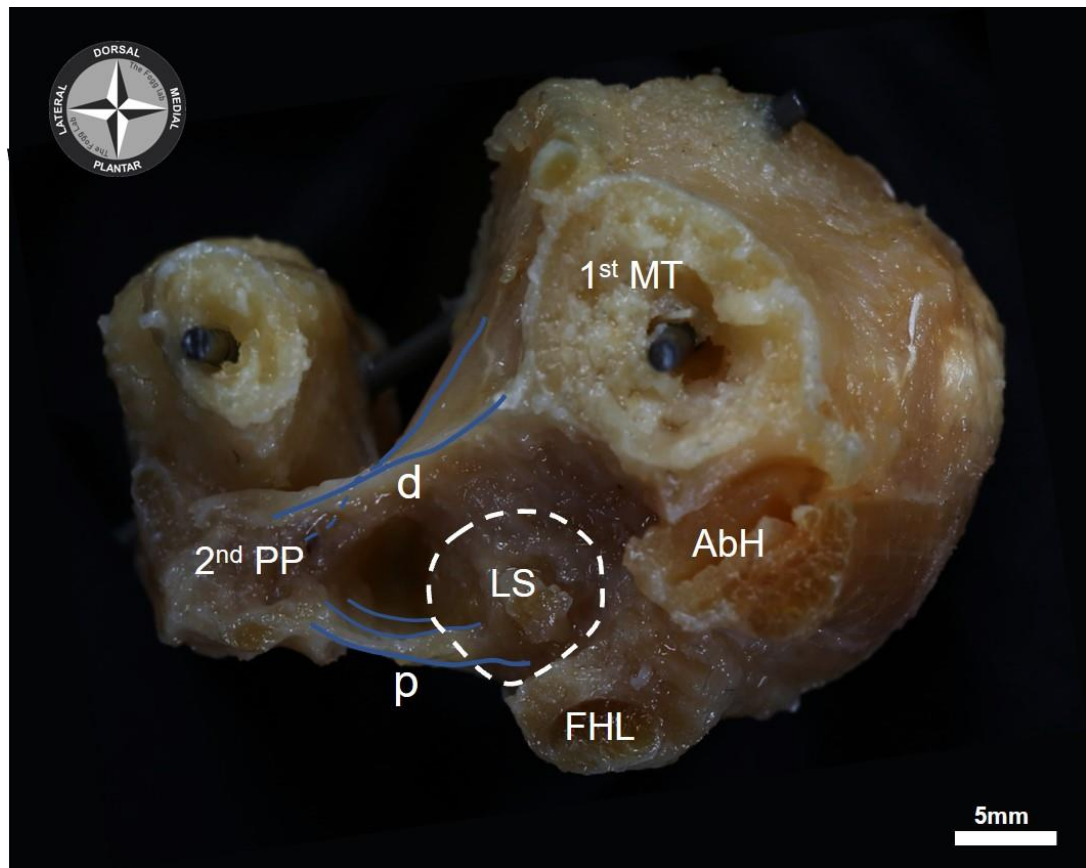


Figure 2.2.2. A proximal view of the first and second MTPJs, with the abductor dissected out to show the dorsal component of the deep transverse metatarsal ligament (d) and the plantar component (p), both attaching laterally onto the second MT PP (2nd PP) and medially onto the lateral sesamoid (LS) and spreading into the extensor hood of the first MT (1st MT) for the plantar and dorsal components respectively. Additional structures of note are the tendons of the abductor hallucis (AbH) and flexor hallucis Longus (FHL).

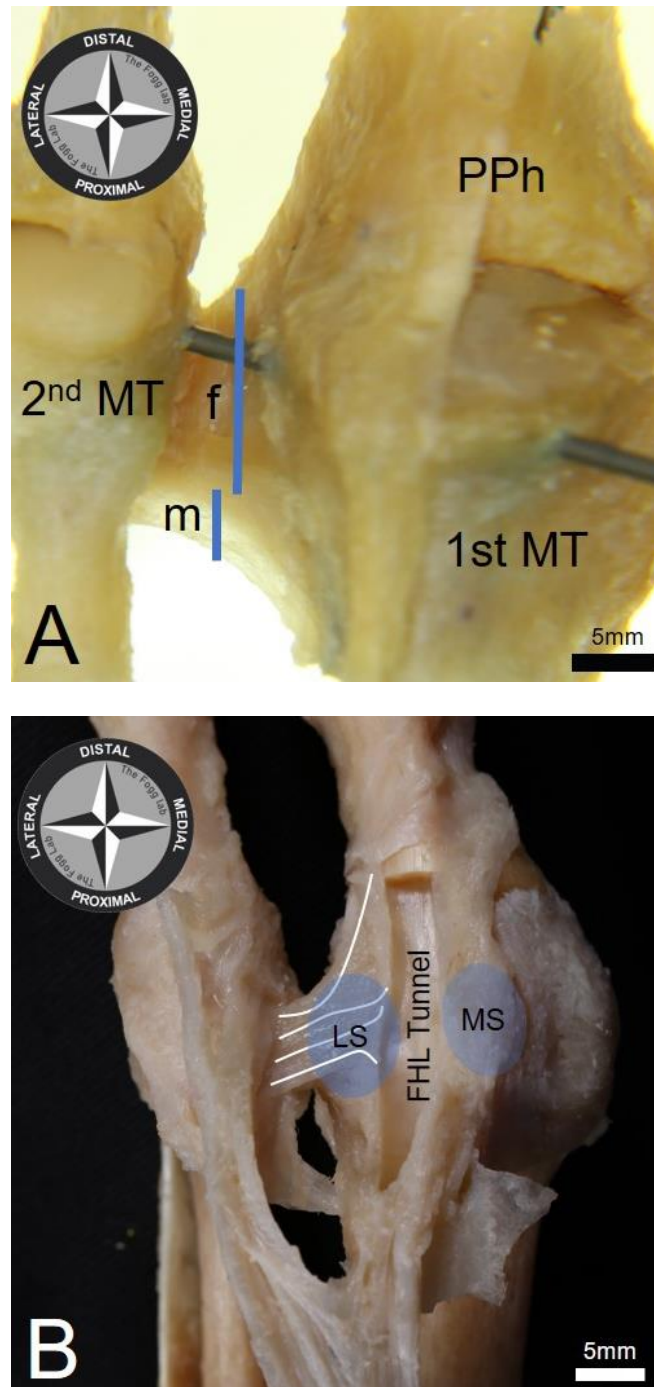


Figure 2.2.3. Views of the dorsal and plantar components of the DTMTL. A - A dorsal view of the first and second MTPJs backlit to provide an appreciation of the membranous proximal third of the dorsal component (m) and the fibrous two thirds distally (f) , B - A plantar view of the first and second MTPJs with the plantar aponeurosis (PA) intact and a thick fibrous plantar component merging into varying tissues laterally including the lateral sesamoid (LS), the plantar aponeurosis , the distal conjoint tendon of the abductor hallucis distally and the FHL tunnel separating the lateral sesamoid from the medial sesamoid (MS).

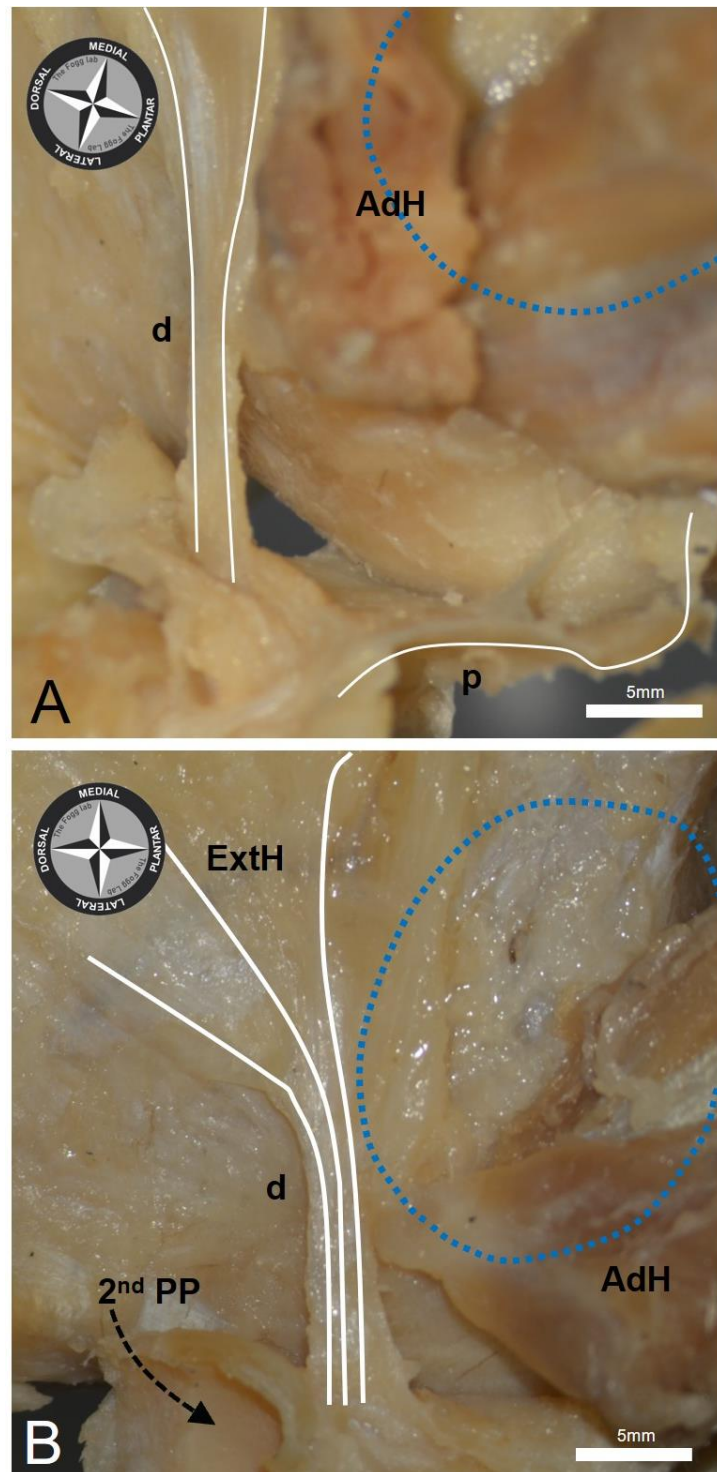


Figure 2.2.4: Dissection microscope views of the dorsolateral aspects of the first MTPJ of two specimens, filled with the stumps of both adductor hallucis (AdH) heads overlying the lateral sesamoid (blue dotted line). In both A and B, dorsal components of the DTMTLs (d) are emphasised. The fibres continued from the 2nd plantar plate (2nd PP) as a condensed ligament, before spreading out to the first MT head medially and the extensor hood (ExtH). The angle of these photos obstructs the plantar component (p) from view.

The fibres of the plantar component ran in a transverse direction between the MTPJs of the hallux and second ray.

The space between the dorsal and plantar DTMTLs was occupied by the incoming tendons of the transverse and oblique heads of the adductor hallucis muscle (Figures 2.2.2 and 2.2.4).

The footprint of the plantar DTMTL was the only component that could be identified onto bone; this attachment covered most of the plantar aspect of the lateral sesamoid (mean area = 26.37mm²; or 24.5% of measurable lateral sesamoid surface; Figure 2.2.5). This footprint was large, and its outline was clear on the lateral sesamoid as it had a strong attachment of uniformly organised thick fibres into the lateral sesamoid. Additionally, the plantar component had fibres connecting from the plantar aponeurosis proximally, whereas at the distal pole of the sesamoid, the fibres joined the conjoined transverse and oblique heads of the adductor hallucis and the sesamophalangeal ligament (Figures 2.2.3 and 2.2.6).

The plantar DTMTL contributed to four structures plantarly:

1. most laterally, plantar to the second MT, to the flexor tunnel of the second toe
2. medial to this, it contributed to the tunnel of the first lumbrical muscle
3. halfway along its length it contributed to a loose and fatty septum that separated the neurovascular structures of the first plantar MT artery and vein from the first common digital branch of the medial plantar nerve, and

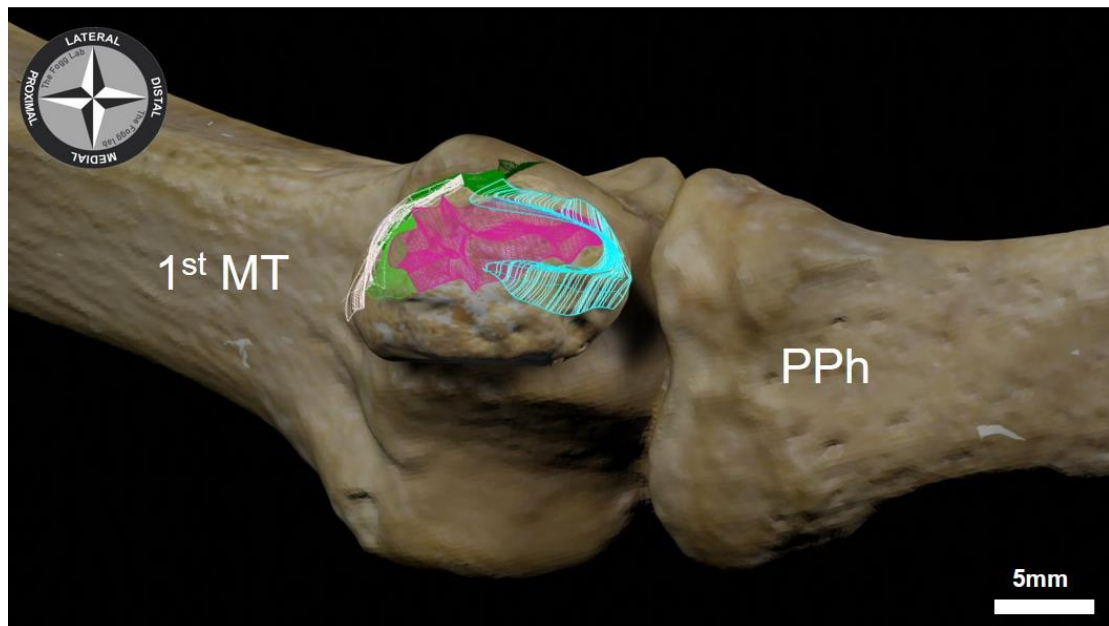


Figure 2.2.5. A plantar view of a three-dimensional model made up from Artec texture scans, micro-CT scans and microscribe footprint data. Highlighting the position of the plantar deep transverse metatarsal ligament footprint (pink) on the plantar aspect of the lateral sesamoid, surrounded by other footprints such as the adductor hallucis footprints (green) and the flexor hallucis brevis footprints (white). The footprint most in contact with that of the deep transverse metatarsal ligament was that of the lateral sesamophalangeal ligament (cyan). 1st MT: first metatarsal bone; PPh: proximal phalanx.

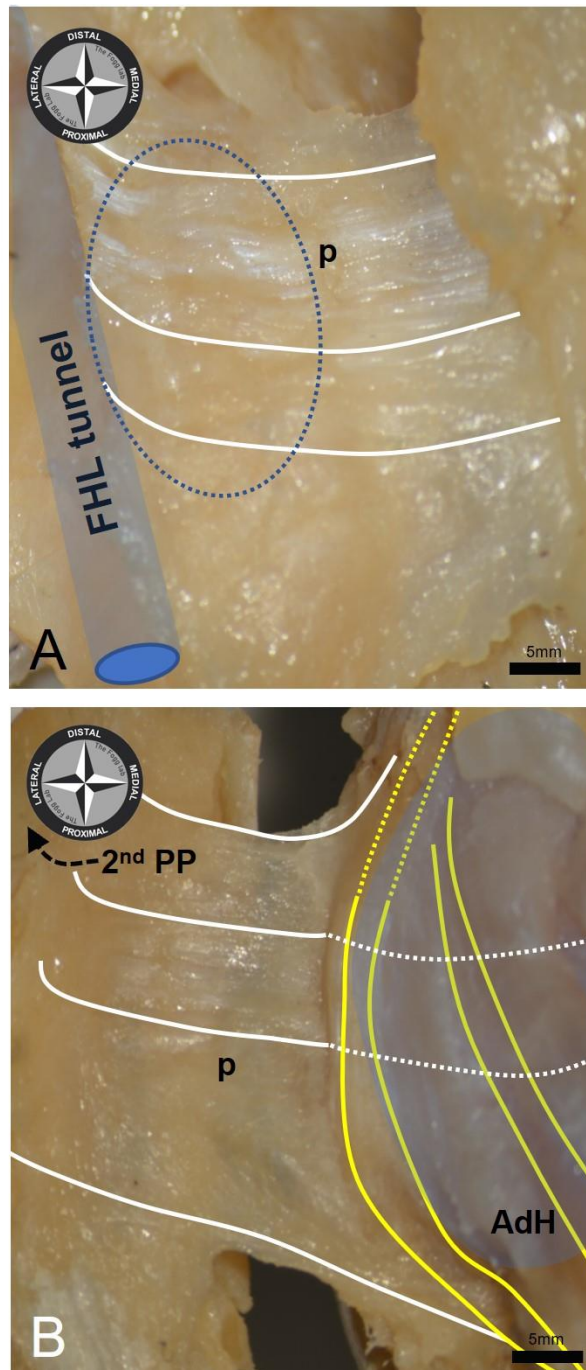


Figure 2.2.6. Dissections of the plantar component of the deep transverse metatarsal ligament (p) A- A plantar view of the medial continuation of the plantar component (white lines) into the margin of the flexor hallucis longus tunnel (blue tube) plantar to the deeper lateral sesamoid (blue dotted oval). B-Dorsal view of the plantar component (p) between the plantar plate of the second metatarsal (2nd PP) and the lateral sesamoid (blue shaded area), with plantar component fibres running deep the lateral sesamoid (dotted white lines) and interdigitating with the distally continuing fibres of the adductor hallucis heads (AdH, yellow lines) and proximally receiving plantar aponeurosis fibres.

4. continued medially and superficial to the intersesamoid ligament, forming the walls and plantar aspect of the flexor hallucis longus tendon tunnel (Figures 2.2.3).

The summary of these findings is as follows: The DTMTL consistently had both thin and membranous dorsal and thick and organized plantar components. These DTMTL components attached laterally to the 2nd MTPJ PP, whereas medially the dorsal component communicated with the extensor aponeurosis with no observable bony footprint, the plantar component attached with a large bony footprint plantarly onto the LS, sandwiching the AdH muscle and tendon between both components. The plantar component contributed to the flexor tunnel of the 2nd MT as well as the tunnels of both the first lumbrical muscle and the septum separating the neurovascular bundle of the first web space, and medially contributed to the walls and plantar aspect of the flexor hallucis tunnel.

2.2.4 Discussion

The deep transverse metatarsal ligament (DTMTL) is a complex structure with numerous attachments. In the current study, the DTML was clearly divided into two components in all cases. These components were previously described (Alvarez *et al.*, 1984; Valvo *et al.*, 1987), however more contemporary research offered different conclusions (Barg *et al.*, 2012; Coughlin *et al.*, 2013; Schneider, 2013). The dorsal component was not recognised in more recent work, but was prominent in all cases and would likely contribute to the functions already attributed to the plantar component (Valvo *et al.*, 1987). The current study demonstrated that both components had numerous connections with neighbouring tissues; this may explain, to some extent, the varied descriptions in the literature and the lack of quantitative data. The poor contemporary recognition of the dorsal component may also explain its likely unintentional transection during lateral soft tissue releases. The most common approach to a lateral soft tissue release is dorsal in the first web space in both open and minimally invasive methods, these have as an aim to reach the lateral sesamoid and contiguous structures (Dalmau-Pastor *et al.*, 2020; Schneider, 2013). By approaching these structures from an incision parallel to the extensor hallucis longus within the first web space, the dorsal component of the DTMTL would be encountered. Interestingly this structure has not been mentioned in the surgical literature reviewed. The dorsal component of the DTMTL then becomes a casualty of the current surgical approach. There are other approaches for lateral soft tissue release, such as the trans-articular

approach, which bypasses the dorsal component of the DTMTL by making a medial approach through the joint. However, this technique has been shown to risk incomplete target sectioning and puts the articular cartilage at risk of damage (Lin *et al.*, 1996; Stamatis *et al.*, 2004). The necessity to transect these structures for HV correction has been questioned (Abdalbary *et al.*, 2016; Schneider, 2013; Valvo *et al.*, 1987; Wang *et al.*, 2015).

The risk in releasing lateral soft tissues may be greater than the potential benefit, particularly due to the potential for avascular necrosis because of the proximity with the underlying neurovasculature (Klos *et al.*, 2021; Valvo *et al.*, 1987), as well as functional side effects, such as first MTPJ instability (Wang *et al.*, 2015), and hallux varus. Anchorage of the lateral sesamoid is the most commonly considered function of the DTMTL (Valvo *et al.*, 1987). The dorsal component, however, was continued dorsally over the first MT head, so would naturally resist internal rotation (pronation) of the first MT, a deformation observed in HV (Coughlin *et al.*, 2013; Saltzman *et al.*, 1997). Damage to the dorsal component may lead to increased risk of internal rotation at the first MT, whilst maintaining and repairing it may reduce the risk of HV or its recurrence post-operatively. Despite this, its importance was not promoted in the reviewed literature.

The attachments of the DTMTL components determine the passive influence they may have (Benjamin *et al.*, 2006). The current study demonstrated that the medial attachment of the plantar component was to the plantar surface of the lateral hallucal sesamoid. This was the only distinct

skeletal attachment of these components. The footprint of the plantar component onto the lateral sesamoid was considerable and had not been well-described previously, despite its importance for joint stability and function being recognised (Coughlin *et al.*, 2013; Kura *et al.*, 1998; Stainsby, 1997; Valvo *et al.*, 1987; Wang *et al.*, 2015). The plantar component was said to be both involved in, and affected by, HV (Abdalbary *et al.*, 2016; Coughlin *et al.*, 2013), suggesting that consideration of its precise anatomy is particularly important.

In addition to the principle attachment to the lateral sesamoid, connections to the plantar aponeurosis proximally, and to the conjoined tendon of the adductor hallucis and sesamophalangeal ligament distally, support earlier work (Valvo *et al.*, 1987). The additional continuation medially of the plantar component to become the walls and plantar floor of the flexor hallucis longus tunnel wasn't identified within the reviewed literature. These additional connections suggest that unintentional disruption of a range of structures may, in turn, disrupt the DTMTL, leading to the array of potential negative outcomes suggested.

The current study explored a small number of specimens in a great amount of detail. The combination of detailed dissection under magnification and digital modelling of observed structures may account for the differences with other studies. The lack of variation in the current study and all reviewed studies suggest that consistency in methodology may be more impactful on results in this area than anatomical variability. It is hoped that the procedures

described in the current study may provide a template for further work in this area. Dissection, by its nature, is destructive. Digitally modelling provided some mitigation of the destructive process, by allowing visualisation of all structures in a virtual environment. Disruption caused by the dissection and modelling process cannot, however, be discounted. Whilst this will not have changed what structures were identified, it may have influenced their orientation. Future works should consider additional techniques, such as histology, macro-sectional anatomy and DiceCT to visualise the soft tissue relations in ways not possible through dissection and to verify the findings of the current study. Within this study, only intra-observer variation was assessed, future studies can also include interobserver observation on key findings.

The results of the current study demonstrate the clear separation of the DTMTL into two components, and its attachment to the lateral sesamoid bone. These anatomical data support a case for active preservation of these components during soft tissue release for HV. The anatomical and functional implications of release of the DTMTL have been considered and may be proven with future biomechanical studies. The greater understanding of the anatomy of the DTMTL components and their relationships provides a basis for a more anatomical approach to the surgical correction of HV. It is hoped that this study will inform further works that will collectively improve postoperative outcomes for those suffering from hallux valgus.

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Part Two, Chapter Three

2.3 The Sesamophalangeal ligaments: An Anatomical Study

2.3.1 Introduction

Restraint and positioning of the hallucal sesamoids (HS) are important for optimal function of the first ray of the foot. Intrinsic foot muscles are only part of the array of structures that may influence HS position. The sesamophalangeal ligaments (SPL) may provide important passive restraint to the HS, but on the rare occasion that they were included in the reviewed literature, their descriptions were inconsistent or incomplete (Crain *et al.*, 2016; Dereymaeker *et al.*, 2011; Kelikian *et al.*, 2011; Linklater, 2012; Schneider, 2013; Yoshioka *et al.*, 1988). Amongst the earliest accounts of the SPLs was an illustration (Gillette, 1872) of the *phalangeosesamoid apparatus* of the hallux, in which they were described as fibrous tissues running from the distal parts of the HS to the base of the proximal phalanx (Gillette, 1872). This illustration has been the foundation of reference for the SPLs in contemporary textbooks (Coughlin *et al.*, 2013; Kelikian *et al.*, 2011). Terminology remains an issue, with the SPLs also referred to as the *phalangeal-sesamoid ligaments* (Nery *et al.*, 2017), the *sesamoid phalangeal ligaments* (Crain *et al.*, 2016), the *phalangeosesamoid ligaments* (Ainhua *et al.*, 2015; Dereymaeker *et al.*, 2011; Waldrop III *et al.*, 2013), or the *capsulosesamoid ligaments* (Thomas *et al.*, 1994). The SPLs were agreed upon, in illustration at least, as bands of fibrous tissue attached proximally to the distal aspects of the HS and distally to the base of the first proximal phalanx (Dereymaeker *et al.*, 2011; Gillette, 1872; Linklater, 2012;

McCormick *et al.*, 2010; Nery *et al.*, 2017). Beyond this basic description, they were rarely considered their own entities and were most often considered as fibrous components of other structures. For example, the SPLs were thought to be investments of the collateral ligaments of the first metatarsophalangeal joint (MTPJ) into the plantar plate (PP), making the medial and lateral edges of the plate stronger (Kelikian *et al.*, 2011; Southerland *et al.*, 2012). Alternatively, they were described as the continuing distal parts of the flexor hallucis brevis tendons after having attached to the HS (Karasick *et al.*, 1998; McCormick *et al.*, 2010). Further still, they have also been considered these same continuations of the flexor hallucis brevis tendons, but conjoined with the distal tendons of the adductor hallucis muscle (AdH) and abductor hallucis muscle (AbH) on their respective sides (Ainhua *et al.*, 2015; Jahss, 1991). The SPLs were most commonly considered to be connected to the PP. To describe the PP is a challenge (Coughlin *et al.*, 2013). Some identified it as the entirety of the thickened aspect of the plantar capsule of the first MTPJ, integrating incoming tendons and attaching proximally to the first metatarsal, and distally to the base of the proximal phalanx (Lucas *et al.*, 2014; McCormick *et al.*, 2010; Richardson, 1987). Other descriptions were minimal, highlighting it as a distal feature between the HS and the base of the proximal phalanx (Linklater, 2012). Despite these variable descriptions, most reviewed studies considered the SPLs as vital parts of the PP, with some even referring to them interchangeably (Crain *et al.*, 2016; Linklater, 2012; Waldrop III *et al.*, 2013). There were clearly issues in the reviewed literature with terminology, and a lack of reproducible methodology in dissection-based studies made it difficult

to compare results. To better understand this complex area, anatomical clarification of the SPLs, and particularly their relation to the PP, is needed. Doing so with a readily reproducible technique will facilitate standardisation of future studies for easier comparison.

In the reviewed literature, the clinical relevance of the sesamophalangeal ligaments was shared with that of the first metatarsal PP, as they were often confounded with one another (Crain *et al.*, 2016; Linklater, 2012). The most referred to injury of the PP was that of “turf toe” (Bowers Jr *et al.*, 1976). Turf toe is caused by hyperextension of a grounded first MTPJ with an added axial load; when the distal MTPJ ligamentous complex is damaged, the damage can be as mild as a sprain and as severe as a complete disruption of the plantar structures (Crain *et al.*, 2016; Linklater, 2012; McCormick *et al.*, 2010). The most likely structures to be damaged in turf toe were the SPLs where they anchor the HS to the proximal phalanx. A diagnostic tool for turf toe was the proximal migration of the HS, even during dorsiflexion of the first MTPJ, suggesting reduction in the tethering provided by tissues attached to the HS (Nery *et al.*, 2017; Waldrop III *et al.*, 2013). Recent advances in MRI and coil technology allowed detailed visualisation of turf toe, identifying any disruption to the tissue mass that may be the SPLs (Crain *et al.*, 2016; Crain *et al.*, 2008; Nery *et al.*, 2017), but not permitting distinction of specific SPLs. Grading the severity of a turf toe was determined by the degree of disruption to the plantar capsuloligamentous complex, made up of the PP, collateral ligaments and overlying tendinous confluences (Crain *et al.*, 2016). The major component was the PP, and it

has been said that “...*in turf toe, the sesamophalangeal ligament is a commonly injured structure and is used interchangeably with the term plantar plate...*”(Crain *et al.*, 2016). The treatment of turf toe was mainly conservative, however surgical treatment, when required, is said to necessitate the restoration of “normal anatomy” (Anderson, 2002; Coker *et al.*, 1978; McCormick *et al.*, 2009). Without clear understanding of the detailed anatomy, the capsuloligamentous complex could be used to only approximate a stable repair; the degree of disruption may also restrict the amount of tissue available (Anderson, 2002; McCormick *et al.*, 2009). Post-operatively, patients often have complaints of persistent pain and stiffness (Anderson, 2002; Clanton *et al.*, 1994). There was a lack of consensus on the surgical management of turf toe (Ortega-Orozco *et al.*, 2021), which may be reflective of the paucity of detailed anatomical information available.

First MTPJ dislocation injuries are relatively rare; (Jahss, 1991). Type III dislocations involve the rupture of the PP at the level of the sesamophalangeal ligaments; Three levels of dorsal dislocation have been defined, and within type III there are sub-divisions with type IIIA with a rupture of the PP between the HS and the proximal phalanx without HS involvement and type IIIB with a rupture of the PP at the same level including a fracture of one of the HS (Ainhua *et al.*, 2015; Jahss, 1991; Killian *et al.*, 1997; Reid *et al.*, 2010). The result of a type III dislocation was that the HS no longer tracked with dorsiflexion of the first MTPJ (Ainhua *et al.*, 2015; Killian *et al.*, 1997; Reid *et al.*, 2010). The dorsal dislocating force acting on the first MTPJ was thought to be distal to the sesamoid complex, rupturing

the “conjoined” tendons, leaving the HS in their anatomic position (Killian *et al.*, 1997). Treatment tended to be closed reduction and maintenance of the hallux in slight plantarflexion during recovery (Killian *et al.*, 1997).

Consideration of open reduction, with occasional release of ligamentous structures (Ainhua *et al.*, 2015; Giannikas *et al.*, 1975; Jahss, 1991; Trikha *et al.*, 2009; Younis *et al.*, 2017), has been recommended for all dorsal dislocations of the first MTPJ (Younis *et al.*, 2017). Scarring and contracture, causing pain and reduced range of motion, were still common outcomes post-operatively (Killian *et al.*, 1997), suggesting that the structures in this area may not be as readily identifiable as some of the literature suggested. Aiming to release the SPLs may be theoretically sound, but the lack of consensus in the anatomical literature and the reports of poor post-operative outcomes suggest that clearer information is needed to inform more accurate surgical interaction with these structures.

The lack of consistent terminology and a consistent, detailed anatomical description of the SPLs causes confusion and crossover within the literature. This study aims to describe the course, relations, and attachments of the SPLs to contribute to an up-to-date anatomical foundation for management of injuries to this region.

2.3.2 Materials and Methods

Feet from embalmed (Genelyn Anatomical Series, Australia; see Appendix 5.1) Body Donors (n = 21; female = 12, male = 9; mean age = 82.1±4.2 years) were examined in accordance with *Part IV of the Human Tissue Act (1992)* and with local ethics approval (project ID: 12292). The sesamophalangeal ligaments are implicated in deformities of the first ray, and are at risk of being targeted during surgical correction, as such exclusion criteria for this study were any signs of previous surgery, any deformation of the first ray in the form of obvious hallux varus or HV. Additionally, if during the dissection process signs of joint degeneration, osteophytes or gout were identified the specimens were excluded.

The feet were CT scanned with a Siemens Biograph 128-slice ultraHD-PET CT scanner (Siemens, Germany; see Appendix 5.11) in order to segment bone (see Appendix 5.5) surfaces for 3D modelling. Skin was removed from the medial aspect of the foot from the base of the first MT to the distal phalanx of the first ray. A medial approach was taken onto the medial surface of the AbH muscle. A fascicular dissection strategy (see Appendix 5.2) was employed to follow along the superficial surface of each structure. Fascicular dissection involved the direct observation of individual tissue fascicles under magnification. Decision-making regarding tissue retention or removal was based on the course of specific fascicles. A surgical microscope (Wild Heerbrugg M651, Switzerland) was used to observe these

tissues under 7-36x magnification, as required. Tissues were dissected until fascicles terminated, either in skeletal attachment, or by converging with other soft tissues. The surface of the AbH muscle and tendon were followed in this fascicular manner, from distal to proximal, to differentiate the AbH tendon from other fascicular structures, including the tendon of the medial head of the flexor hallucis brevis (FHB) muscle. The AbH muscle was then sectioned at its musculo-tendinous junction and the isolated AbH tendon was reflected distally. The same procedure was carried out for the medial head of the FHB muscle.

From a plantar lateral approach in the first webspace, the same procedure was carried out for the AdH muscle, the lateral head of the FHB muscle, the deep transverse metatarsal ligament (DTMTL) and the plantar aponeurosis. This allowed for the exposure of both the medial and lateral SPLs. Using the same fascicular approach, the fascicles of each SPL were carefully traced from attachment to attachment. At each stage of dissection, the target tissues were described and photographed (EOS 5D mark III, Canon, Japan).

Once the dissection of each structure of interest was complete, measurements were made of each prior to dissection of other structures, or of their attachment. The maximal height and width of each SPL, abductor and adductor tendon were measured in the coronal plane with the use of digital calipers. The lengths of the sesamophalangeal ligaments were measured in

the sagittal plane with the use of digital calipers and tabulated. All measures were made in triplicate to improve the intraobserver reliability of the data. All images were reviewed with an expert team including anatomists and clinicians, but measurements done in triplicate were carried out by the author as a single intra-observer study (Figure 2.3.1).

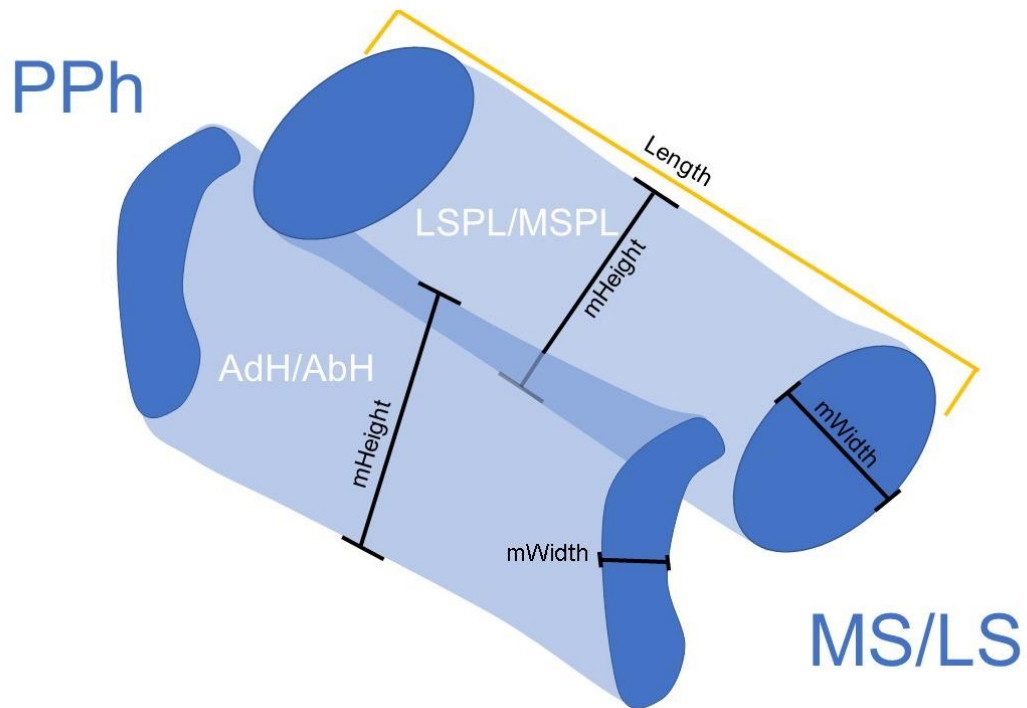


Figure 2.3.1. Schematic representing measurement protocol for measuring the abductor hallucis (AbH) or adductor hallucis (AdH) muscle fibres, as well as the underlying lateral sesamophalangeal (LSPL) or medial sesamophalangeal (MSPL) ligaments. The measures were taken between the medial (MS) or lateral (LS) sesamoids and the proximal phalanx (PPh), at the highest (mHeight) and widest (mWidth) points of the fibrous structures were measured to determine a rough cross-sectional area. The lengths between attachment points were also noted.

At each level of dissection, attachments to bone were carefully clarified by removing any soft tissue, including periosteum, at the periphery of each attachment “footprint”. If this peripheral tissue was associated with another structure of interest, the border was marked with ink. Each target structure was cut to leave a minimal stump, facilitating direct observation of the complete circumference of the footprint at once.

Sesamophalangeal ligament (SPL) footprints on both HS and the proximal phalanx were outlined and modelled into a virtual 3D space using a digital microscribe (Microscribe G2X, ImmersionCorp, USA; see Appendix 5.3). Adjacent footprints that included close relation to those of the SPL (overlap, shared border, etc.) were also mapped, but quantitative values were not included as part of this study. These included the AdH and AbH muscles and the metatarsophalangeal ligaments. The microscribe recorded the 3D coordinates of a single point into a virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA). A sequence of points located along a surface were converted into a digital line, and a series of digital lines used to render a model of a surface in the virtual environment. Utilising this process for each footprint not only rendered them in 3D, but allowed measurements of each to be taken, inclusive of their curvature. Footprints were modelled in triplicate to facilitate assessment of the accuracy and reproducibility of the process. The area and perimeter of each footprint was measured in the virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA). To facilitate this process for all relevant attachments,

footprints were dissected off once their modelling sequence was complete. This facilitated clear observation, modelling and measurement of subsequent footprints.

The digital models of each footprint were then matched to their respective CT data. These data had been segmented (see Appendix 5.5) and meshed to create models of the HS, proximal phalanx and first metatarsal. Overlaying the bone models with the corresponding footprint models allowed visualisation of the complete array of footprints in three dimensions. The virtual environment software (Rhinoceros 4.0, Robert McNeel and Associates, USA) allowed for area measurements of the non-articular surface of each HS and of each footprint model. Analysis of these data allowed for consideration of each HS attachment as a percentage of the available HS surface area. To aid 3D visualisation of data, surface scans of relevant skeletal surfaces were created using a laser surface scanner (Artec3D, Luxembourg; see Appendices 5.6-5.9).

To determine the accuracy and reproducibility of the measurements and footprint modelling undertaken, all measurements and footprint models were done in triplicate. The data from each round of measurement/modelling were analysed for statistically significant differences at a standard confidence interval ($p = 0.05$).

2.3.3 Results

The sesamophalangeal ligaments (SPLs) were shown to be present in all specimens as thick bands of fibrous tissue with an organised fascicular appearance, longitudinally coursing from the distal poles of their respective sesamoid to the base of the proximal phalanx. The SPL proximal attachments occupied a large part of the respective HS. The mean area of medial SPL attachment to the medial HS ($71.68 \pm 31.57 \text{ mm}^2$; 35% of HS surface) was not significantly different to the mean area of the lateral SPL on the lateral HS ($48.79 \pm 8.27 \text{ mm}^2$; 36% of HS surface; $p > 0.05$). The relatively large standard deviation for each proximal attachment area, however, suggested differences between individuals worth noting.

The medial SPL was identified in all cases ($n=21$; 100%) and was consistently in need of careful separation from specific neighbouring structures (Table 2.3.1). The mean cross-sectional areas of the medial SPL and AbH distal tendon were $26.73 \pm 5.09 \text{ mm}^2$ and $25.54 \pm 8.27 \text{ mm}^2$ respectively. There were, however, clear differences in type of attachment and footprint shape both proximally (to the HS) and distally (to the proximal phalanx). These differences were classified into two types. Type I attachments of the medial SPL were smaller in mean area proximally (40.11 mm^2) and distally (29.39 mm^2) than those of Type II attachments proximally (103.25 mm^2) and distally (82.34 mm^2). In all cases ($n = 21$; 100%) the proximal and distal attachments of the medial SPL were of the same type.

Table 2.3.1. List of structures contiguous with each SPL. These structures were closely associated with the SPL, fascicular dissection was necessary to differentiate them from one another. SPL: Sesamophalangeal ligament, AbH: Abductor hallucis, FHB: Flexor hallucis brevis, FHL, Flexor hallucis longus, AdH: Adductor hallucis, MTPJ: Metatarsophalangeal joint.

	Medial SPL	Lateral SPL
Medial Aspect	AbH tendon	Intersesamoid ligament
	FHB medial head tendon slips	FHL tunnel
Lateral Aspect	FHL tunnel	AdH tendon
	Intersesamoid ligament	FHB lateral head tendon slips
Plantar Aspect	Plantar aponeurosis	Plantar aponeurosis
	AbH tendon in part	AdH tendon in part
	MTPJ capsule	MTPJ capsule

Each Type I medial SPL was attached proximally to a more circular area on the distal third of the medial HS. The distal attachment of each Type I medial SPL was to the edge of the plantar medial tubercle of the proximal phalanx; few fascicles extended plantarly beyond this attachment and were limited dorsally by the MTPJ capsule. This attachment was immediately lateral to the distal AbH tendon attachment (Figure 2.3.2A).

Type II medial SPL attachments were larger, more irregular and extended further than Type I attachments. The proximal attachment was centred on the distal third of the medial HS but included proximal extensions to the HS attachment of the plantar aponeurosis and more medially along the HS (Figure 2B). The more medial extent of the proximal attachment required the removal of the HS attachment of AbH tendon to completely visualise the footprint. Each Type II medial SPL had an elongated distal attachment along the base and shaft of the proximal phalanx (Figure 2.3.2B). This continued distally and laterally enough to regularly engage with the medial surface of the flexor hallucis longus tunnel (Figure 2.3.2B).

Type II medial sesamophalangeal ligament attachments were those that varied from the norm, with more extensive or complex attachments, finding irregular edged attachments to the distal third of the medial sesamoid,

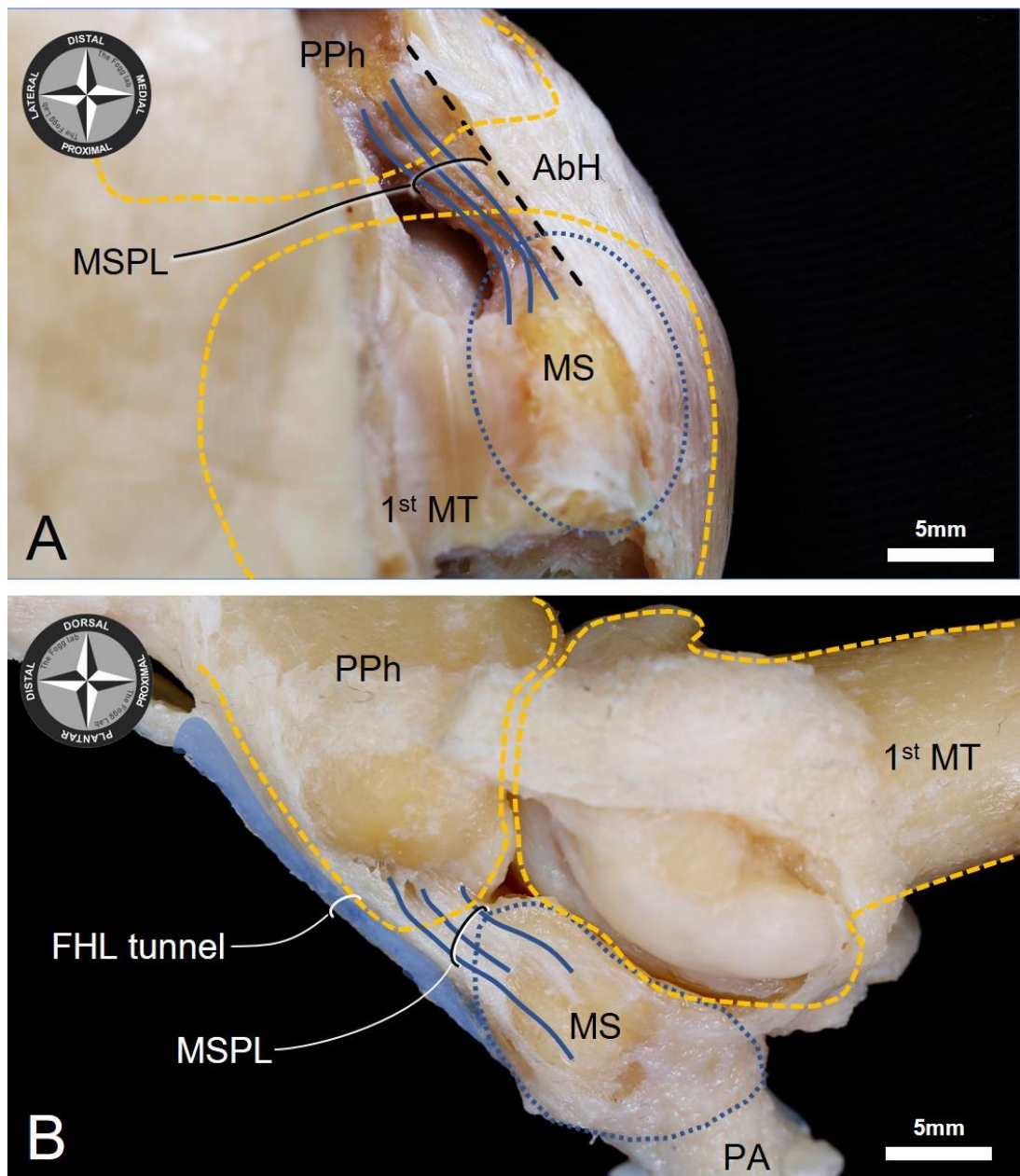


Figure 2.3.2. A – a plantar view of the medial sesamoid (MS) (in blue dots), a type I medial sesamophalangeal ligament (MSPL) is attaching onto the medial sesamoid proximally and the base of the proximal phalanx (PPh) distally. Contiguous to it on its medial aspect, and slightly obstructing it from view, is the abductor hallucis (AbH) tendon running its course onto the sesamoid and the medial aspect of the medial tubercle of the proximal phalanx. B- a medial view of a cleared MTPJ leaving just the MSPL and the plantar aponeurosis (PA) on the proximal pole of the MS. Here a type II irregular MSPL is attached via long fascicles onto the plantar aspect of the proximal phalanx (PPh) and the flexor hallucis longus tunnel (FHL tunnel). The outlines of the PPh and first metatarsal (1st MT) are in yellow dashes in both images.

and elongated attachments along the plantar medial aspect of the base and shaft of the proximal phalanx (Figure 2.3.2B).

The lateral SPL was identified in all cases (n=21; 100%) and was consistently in need of careful separation from specific neighbouring structures (Table 2.3.1). The mean cross-sectional areas of the lateral SPL and AdH distal tendon were $32.02 \pm 8.55 \text{ mm}^2$ and $27.01 \pm 53.45 \text{ mm}^2$ respectively. There were, however, clear differences in type of attachment both proximally (to the HS) and distally (to the proximal phalanx). These differences were classified into two types. Type I attachments of the lateral SPL were smaller and less diffuse than those of Type II attachments. The bony attachment footprints were similar between types: both types had a mean area proximally of $48.79 \pm 8.27 \text{ mm}^2$ and $45.76 \pm 2.07 \text{ mm}^2$ distally. In all cases (n = 21: 100%) the proximal and distal attachments of the lateral SPL were of the same type.

Each Type I lateral SPL was attached proximally to a compact area on the distal third of the lateral HS. This attachment was dorsal to, but closely associated with the HS attachment of the distal AdH/conjoined tendon (Figure 2.3.3A). The distal attachment of each Type I lateral SPL was to the medial edge of the plantar lateral tubercle of the proximal phalanx. This attachment was immediately medial and plantar to the distal AdH tendon/conjoined tendon attachment on the proximal phalanx (Figure 2.3.3A).

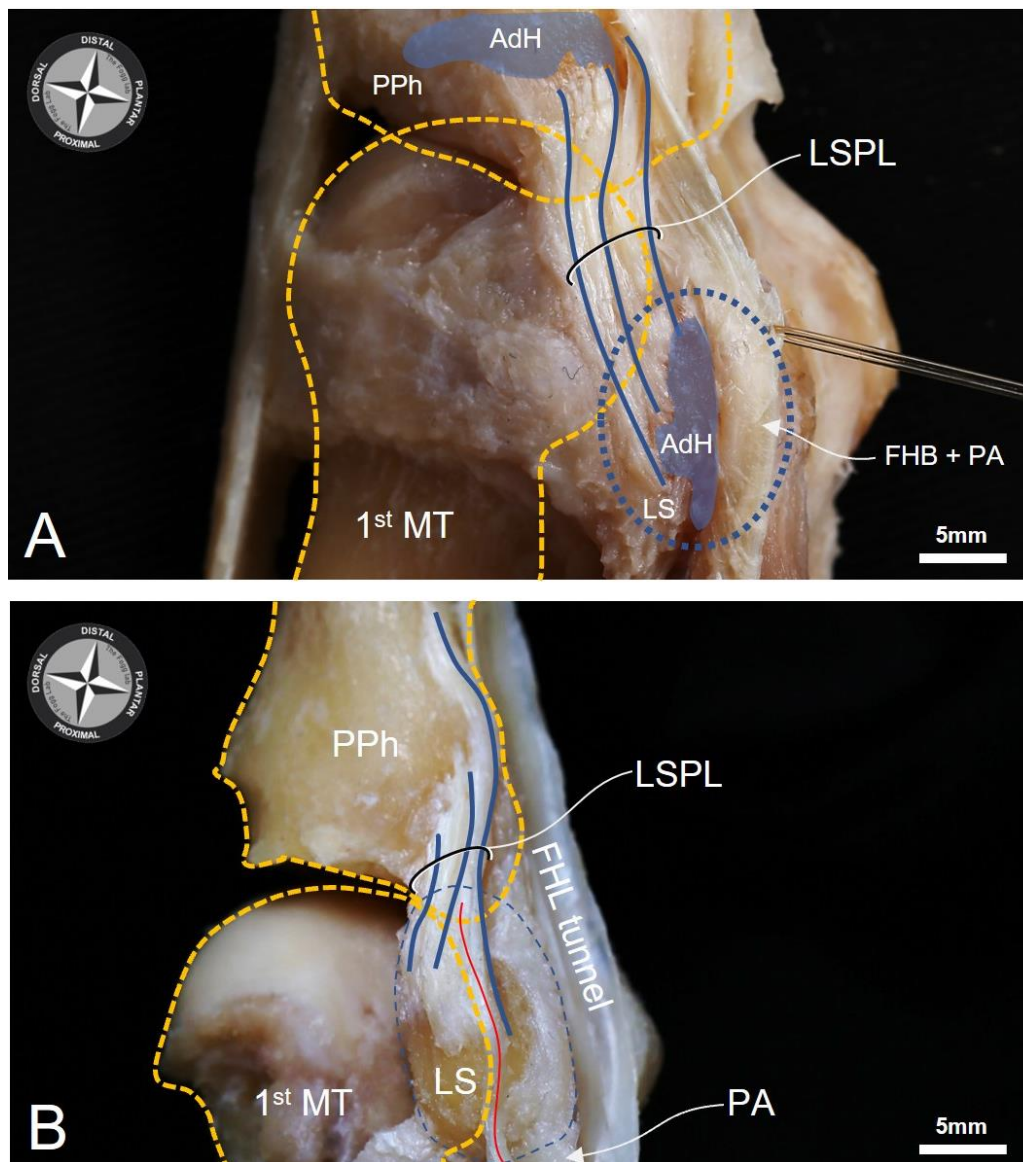


Figure 2.3.3. A - A plantar lateral view of a type I lateral sesamophalangeal ligament (LSPL) extending with regularity proximally along the lateral sesamoid (LS), previously hidden by the adductor hallucis (AdH) tendon which had attachment sites proximally and distally (blue shadows), medially some continuing fibres of the flexor hallucis brevis (FHB) and plantar aponeurosis (PA) are being reflected medially into which some of the LSPL fibres are interdigitating. B – A plantar lateral view of a type II LSPL with irregular extensions from a type I footprint, extending proximally being contributed to by the PA (red line) and distally with a long medial component along the plantar aspect of the proximal phalanx (PPh) alongside the flexor hallucis tunnel (FHL tunnel).

Type II lateral SPL attachments were larger, more irregular and extended further than Type I attachments. The proximal attachment was centred on the distal third of the lateral HS but included proximal extensions to the HS attachment of the plantar aponeurosis and more dorsally along the HS (Figure 2.3.3B). Each Type II lateral SPL had an elongated distal attachment along the base and shaft of the proximal phalanx (Figure 2.3.3B). The distal continuation was most prominent plantarly (Figure 2.3.3B).

Type II medial sesamophalangeal ligament attachments were those that varied from the norm, with more extensive or complex attachments, finding irregular edged attachments to the distal third of the medial sesamoid, and elongated attachments along the plantar medial aspect of the base and shaft of the proximal phalanx (Figure 2.3.2B).

Both SPLs had a degree of crossover in all specimens (n=21; 100%). The medial SPL contributed fascicles that coursed obliquely and laterally in a more plantar plane, with some fascicles coursing from the lateral aspect of the distal pole of the medial HS to attach onto the central portion of the base of the proximal phalanx (Figures 2.3.4 and 2.3.5). The oblique fascicles from the lateral SPL were in a more dorsal plane and coursed from the medial aspect of the distal pole of the lateral HS onto central portions of the base of the proximal phalanx (Figure 2.3.3). These “crossover” fascicles from both SPLs were not as robust as the more longitudinal fascicles. There was no

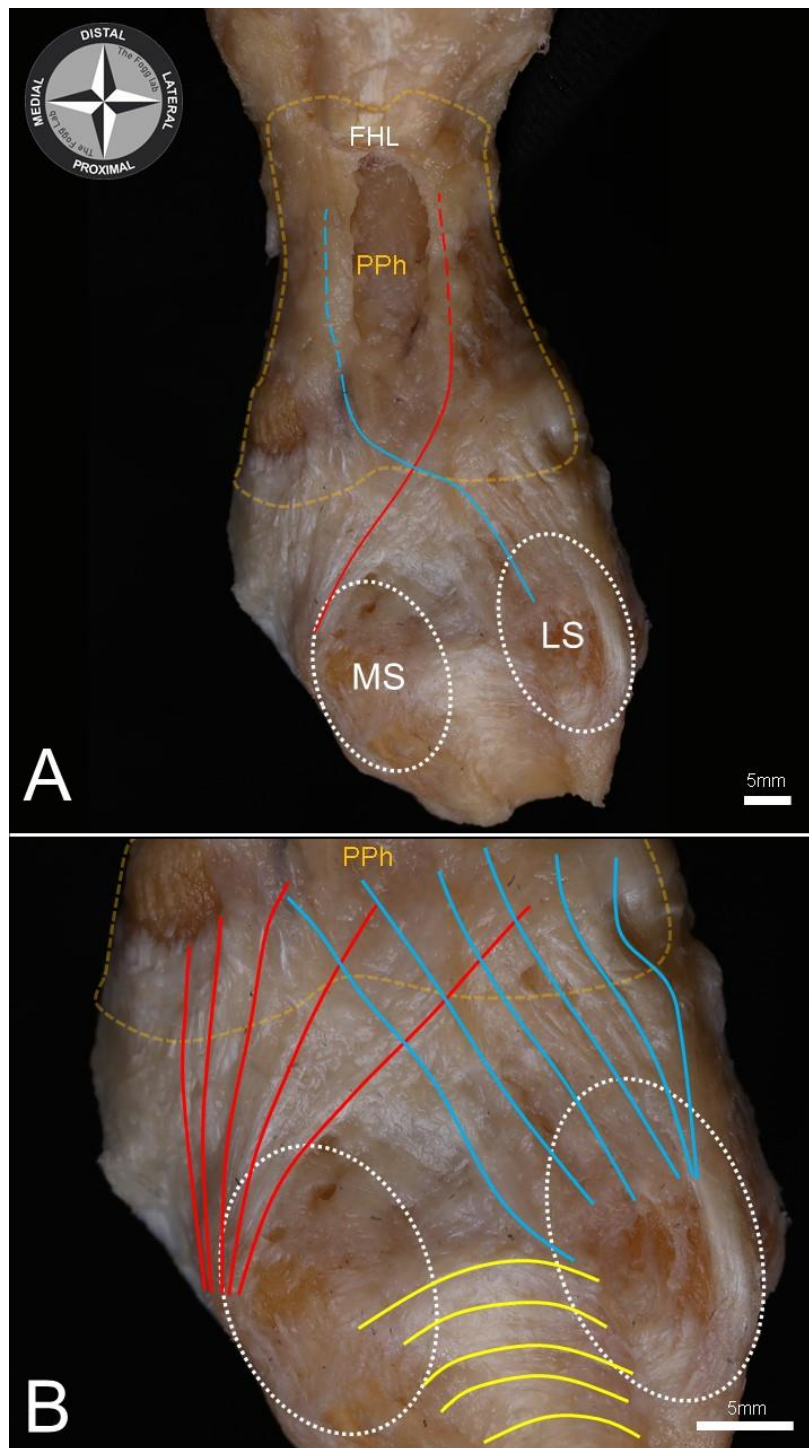


Figure 2.3.4. Plantar view of the sesamophalangeal interval. A - view of extensive crossing of fibres (red and blue lines) from the medial (MS) and lateral (LS) sesamoids to the proximal phalanx (PPh orange dashed line). And into the disorganised tissues along the plantar aspect of the PPh and around the FHL tunnel (Red and blue dashed lines). B - a closer view of the same specimen, with more detail on the medial sesamophalangeal ligament (red) and the lateral sesamophalangeal ligament (blue), and the intersesamoid ligament (yellow).

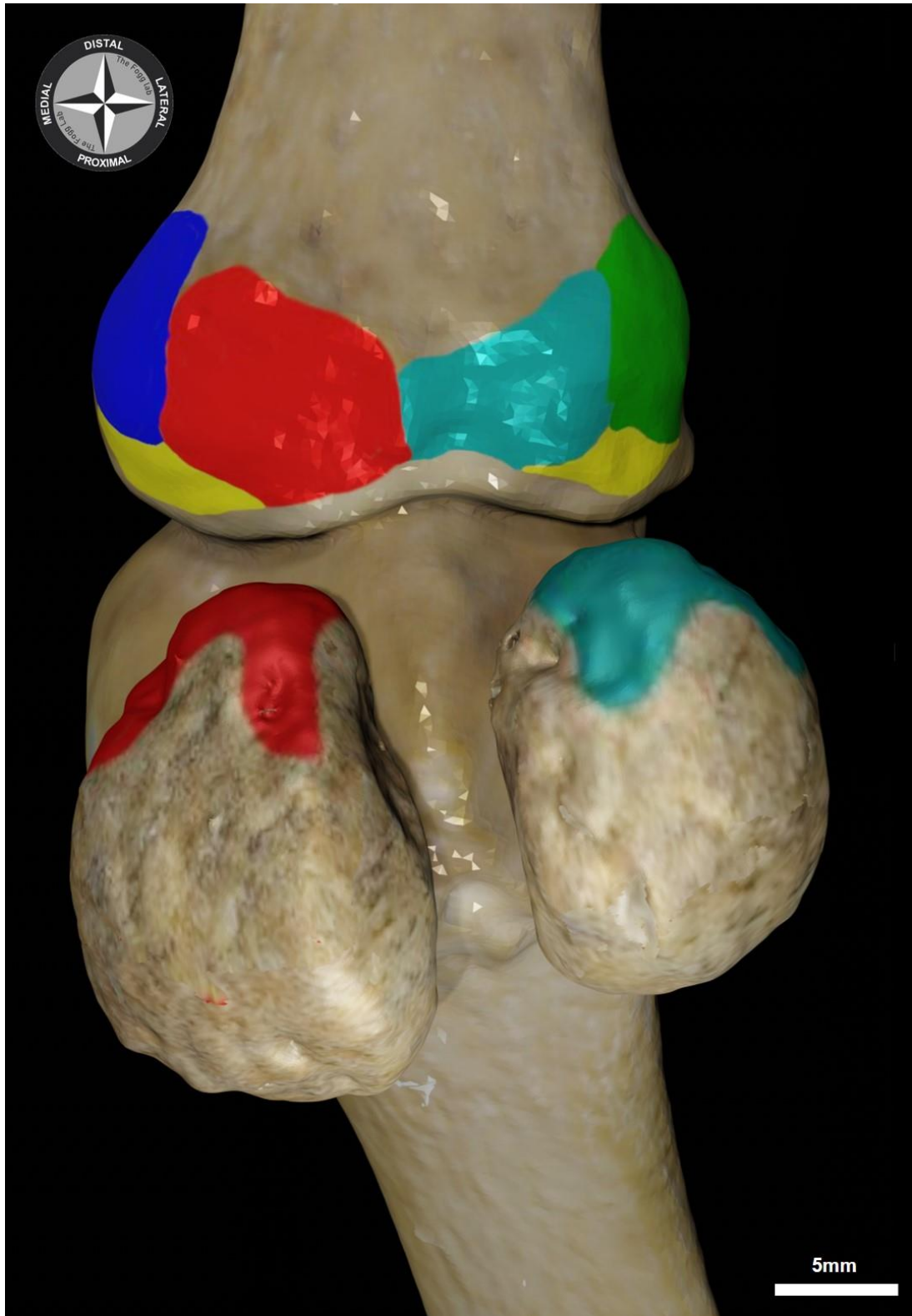


Figure 2.3.5. A plantar view of a rendering from CT an Artec 3D scan and microscribe data, with the footprints of the medial and lateral sesamophalangeal ligaments (red and cyan), the distal footprints of the adductor (green) and abductor (blue) hallucis as well as footprints of the metatarsophalangeal ligaments (yellow).

consistent difference in oblique fibres between types. The oblique fibres sat deep to the smoother and more fibrous tissues of the flexor hallucis longus (FHL) tunnel, seemingly supporting the dorsal roof of the tunnel (Figures 2.3.5 and 2.3.6).

In summary the SPLs were consistently identified with large bony footprints in all specimens longitudinally coursing between the poles of both of the HS to the respective sides at the plantar base of the PPh. The attachments to both the HS and the PPh were classified into two types with diffuse and regular edged attachments. Both the lateral SPL and medial SPL had fibre crossover, with oblique fibres filling the plantar aspect of the first MTPJ between the HS and the PPh, running dorsal to the dorsal roof of the FHL tunnel, separating it from the first MTPJ synovial lining.

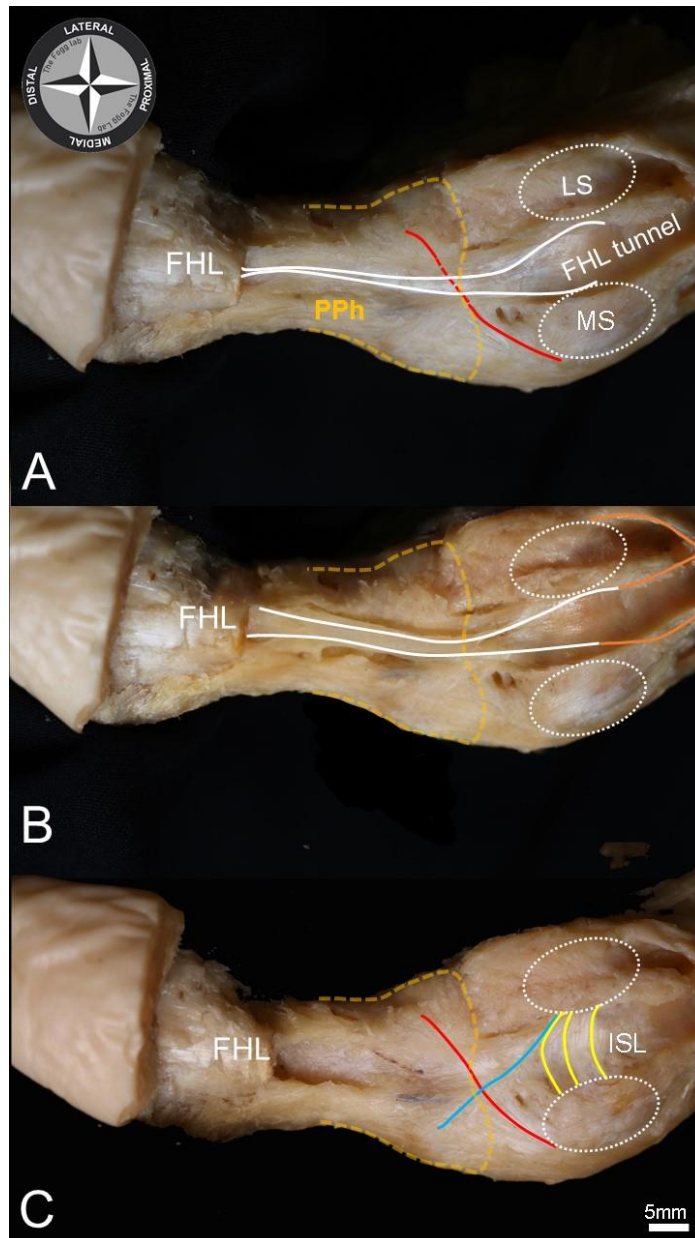


Figure 2.3.6. Plantar views of the same hallux through the removal of the flexor hallucis longus tunnel (FHL tunnel) roof fibres (white lines). A- Specimen dissected down to the FHL tunnel roof, with the medial (MS) and lateral (LS) sesamoids identified, the edges of the proximal phalanx (PPh, orange dashed line) palpated, a few oblique fibres of the medial sesamophalangeal ligament (red) are identified crossing dorsal to the FHL tunnel. B- the FHL tunnel roof is lifted away from the more dorsal tissue, as a single smooth and fibrous layer, with multiple slips identified proximally between the hallucal sesamoids joining the plantar aponeurosis (orange lines) C- The FHL tunnel removed highlighting the medial (red) and lateral (cyan) sesamophalangeal oblique fibres that cradled the tunnel dorsally, proximally the FHL tunnel slips embedded into parts of the PA and the inter-sesamoid ligament (ISL, yellow).

2.3.4 Discussion

The sesamophalangeal ligaments (SPLs) have been variably described and named. The current study demonstrated that there were two distinct, clearly demarcated SPLs. For each, two distinct types were identified, with Type I SPLs exhibiting smaller and more compact attachments at both ends. Type II SPLs had larger, elongated attachments at both ends, increasing their interactions with neighbouring tissues. The fascicles of the SPLs were clearly separated from the overlying fibres of the tendons of the AbH muscle medially and the AdH muscle laterally in all specimens. Previous studies suggested that these ligaments were components of the first MTPJ PP, conjoined tendon, FHB tendon, or other capsular thickenings (Ainhua *et al.*, 2015; Jahss, 1991; Karasick *et al.*, 1998; Kelikian *et al.*, 2011; McCormick *et al.*, 2009; Southerland *et al.*, 2012). The separation from these tendons supports their identification as distinct structures. The current study demonstrated that both were distinct, organised fascicular structures coursing from one skeletal attachment to another, i.e., ligaments. Terminology is particularly important here; one study even used multiple terms in the report, conflating *short sesamoidal phalangeal ligaments* with *conjoined tendons* and a *conjoined phalangeal sesamoidal tendon* (Killian *et al.*, 1997). This illustrated the need for clarity and consistency in such a small complex area. The current data also strongly supporting a distinction being made between the SPLs and the 1st plantar plate. Whilst the plantar plate for the 1st MTPJ may be considered a convergence of various fibrous tissues (Coughlin *et al.*, 2013; Kelikian *et al.*, 2011) rather than

distinct “plate” as seen in the lesser toes (Gregg *et al.*, 2007a; Johnston *et al.*, 1994), the SPLs are well-defined, separate structures. Their close association with other structures, particularly overlying tendons, may make them difficult to identify, but the current data suggest that they should be given individual consideration.

There may have been ambiguities in previous work due to the very close relationships that the SPLs have with their respective surrounding tissues. The adherent border identified between the SPLs and their respective AdH or AbH tendons (Figure 2 and 3), made differentiating between them difficult unless carrying out a fascicular dissection. This puts forward potential for complications during the targeting of these tendons. The AbH distal tendon is targeted for conditions such as hallux valgus (Brenner, 1999), clubfoot deformity (Fadel, 2019), and metatarsus varus (Mitchell, 1980). The adductor hallucis distal tendon is targeted in hallux valgus correction (Pfeffer *et al.*, 2017; Southerland *et al.*, 2012). Considering the frequency at which the SPLs were confused for these overlying tendons in anatomical studies, and the fact that they have not been accurately described before suggests that accurately identifying the SPLs in an operative setting is far more difficult.

The central area of attachment on the plantar base of the proximal phalanx has been described to house a weak transverse band between the two SPLs (Crain *et al.*, 2016; Kelikian *et al.*, 2011), the space between the

two ligaments is illustrated as empty in most texts. This research identified components of the SPLs that were not purely longitudinal and crossed to their opposing SPL, attaching in the central portion of the base of the proximal phalanx (Figures 2.3.4-2.3.6), previously thought to be devoid of any attachment other than the joint capsule. These crossing fibres were found to be thin and, as such, would substantiate that the space between the longitudinal fibres is weak. In cases of severe hyperextension injury, as in Jahss dislocations (Jahss, 1991), In type IIA with an inter-sesamoid ligament tear, or in type III where all structures in the sesamophalangeal interval rupture, these oblique fibres would be damaged. The repair of this surface may be required as part of the surgical management of Jahss dislocations. The relationship of the oblique SPL fibres with the FHL tunnel (Figure 2.3.6) suggests a supporting role to the dorsal surface, creating a thickening of tissue between the FHL tendon and the first MTPJ space. In the event of SPL oblique damage, there may be associated damage to the FHL tunnel.

The cross sectional area of a ligament or tendon is a crucial pre-requisite factor for estimation of biomechanical properties, such as Young's modulus, and strain energy density (Ge *et al.*, 2020). This can be used to estimate the strength and failure load of a ligament or tendon. The technique used in this study assumed an ellipse shape for the fibres measured, this has been carried out before and is a relatively reliable, repeatable and non-destructive method (Ge *et al.*, 2020; Haut *et al.*, 1969). The current preliminary data show that the cross-sectional area of the SPLs are not significantly different from those of the AdH or AbH, and are likely to be of

equal importance within the sesamophalangeal interval, and are likely among the main structures put under stress during hyperextension injuries, such as turf toe or type III Jahss dislocations, confirming previous work (Crain *et al.*, 2016).

Whether the adductor and abductor hallucis tendons consistently attach to just the base of the proximal phalanx, or to the HS, or both has been a matter of contention, compounded by differing descriptions of the attachments of the AdH (Coughlin, 1996; Schneider, 2012; Wulker, 2000) and AbH muscles (Agawany *et al.*, 2010; Brenner, 1999). The contiguous relationships the tendons have with the SPLs, consistently identified in the current study, were not reported in the reviewed literature. The SPLs form distinct connections between their respective HS and the proximal phalanx. They are therefore likely to play a similar mechanical role, albeit passively, between these bones as their related intrinsic muscle (AbH or AdH muscle). Both should be considered surgically, relative to the individual situation.

This research was not without limitations. The Donors studied came from a sample population with a high mean age (82.1 years), which may suggest that the small structures studied to be smaller, thinner and/or weaker. The consistent findings of the current data suggest that this was not an issue, but comparisons with a younger sample population would be welcomed. Within this study, only intra-observer variation was assessed, future studies can also include interobserver observation on some key

findings. The combined dissection and digital modelling approach facilitated the detailed assessment of the SPLs in three dimensions and allowed for a reconstructive approach to visualising dissection data. Despite these advantages, the dissection process remains destructive. Future studies could include sectional analysis (macro-sections, histology, diceCT, etc.) to observe tissue interrelations with less investigative disruptions. Comparison data from these approaches would provide a more comprehensive account of the detailed anatomy. Biomechanical studies of the relative strengths of the SPLs and the tendons would clarify which is most crucial in resisting hyperextension and transmitting force to the hallux.

The medial and lateral SPLs have been clearly defined as distinct structures with close relations to active and passive elements of the first ray complex. These data will contribute to improved anatomical understanding of this complex, which will inform continued improvements in the clinical management of conditions such as turf toe and Jahss dislocations.

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Part 3

Other Hallucal Sesamoid Attachments

Part Three, Chapter One

3.1 Abductor Hallucis Muscle

3.1.1 Introduction

The tendon of the abductor hallucis (AbH) muscle is said to twist to attach onto the medial and plantar margins of the medial sesamoid (Wong, 2007) and surrounding plantar plate (PP), or to bypass the medial sesamoid entirely to distally attach to the base of the proximal phalanx (Agawany *et al.*, 2010; Brenner, 1999). It has been said that some of the superomedial fibres connect superiorly to the transverse lamina of the extensor hood (Pfeffer *et al.*, 2017), or into the first metatarsophalangeal joint (MTPJ) (Agawany *et al.*, 2010; Brenner, 1999; Theumann *et al.*, 2002; Valvo *et al.*, 1987). Four main variations in distal AbH attachment have been described (Agawany *et al.*, 2010; Brenner, 1999; Kelikian *et al.*, 2011; Schwagten *et al.*, 2020; Wong, 2007). Brenner (1999) described three types that best encompass the range of variations, where the amalgamated tendons of the flexor hallucis brevis (FHB) and AbH attached distally, either to the proximal phalanx alone (Type A), to both the proximal phalanx and medial sesamoid (type B), or to the medial sesamoid alone (type C; (Brenner, 1999), with 59.6% of the sample to be of type B. Elsewhere (Agawany *et al.*, 2010), the dominant type observed (46.7%) was more akin to type A, with no connection to the medial sesamoid (Agawany *et al.*, 2010; Brenner, 1999).

The inconsistencies within these descriptions, and the “poor” detailed anatomical references of the AbH (Brenner, 1999) could be due to the inconsistent methodologies utilised, as there is currently no gold standard for dissection approach and parametric measurements of the AbH and its attachments, making it difficult to compare studies more broadly and for accurate functional predictions.

The abductor hallucis (AbH) distal tendon was considered in a number of surgical procedures, such as for the correction of recurrent clubfoot deformity (Fadel, 2019) and AbH tendon transfer (Hawkins, 1971), as released in metatarsus varus (Mitchell, 1980). Also notable was the practice of medial capsular reefing, or medial capsulorrhaphy, at the first metatarsophalangeal joint (MTPJ). This was a step during many hallux valgus correction surgeries (Coughlin *et al.*, 2005; Kitaoka *et al.*, 1991; Quill Jr, 2005; Wuelker, 1994), where a section of the medial aspect of the first MTPJ was tightened, by sectioning out a strip of tissue (Wuelker, 1994), or an ellipse of capsule (Kitaoka *et al.*, 1991), or by means of various cuts and folds to the capsule (Quill Jr, 2005; Renehan *et al.*, 2021). This was of interest as the medial aspect of the first MTPJ capsule was a reported distal attachment point for the AbH (Brenner, 1999; Theumann *et al.*, 2002). The plantar half of the capsule was also reported to be re-enforced by the AbH (Agawany *et al.*, 2010; Brenner, 1999; Joseph *et al.*, 2007), yet the AbH is rarely mentioned during medial capsulorrhaphy.

In all of the procedures involving the AbH, the exact location of the tendon and its attachments was deemed vital, especially to safely avoid damaging it during medial capsulorrhaphy (Quill Jr, 2005), or to avoid damaging surrounding structures during AbH tendon transfers (Hawkins, 1971; Leemrijse *et al.*, 2008) or tenotomies for recurrent clubfoot deformity (Fadel, 2019).

This research aimed to map the attachments of the AbH distally to the medial sesamoid and the proximal phalanx, providing a more accurate means for AbH identification during surgery, and increasing understanding of the role the AbH plays in the pathomechanisms of hallux valgus and hallux varus.

3.1.2 Material and Methods

Feet from embalmed (Genelyn Anatomical Series, Australia; see Appendix 5.1) Body Donors (n = 32; female =15, Male = 17; mean age = 81.3 years) were examined in accordance with *Part IV of the Human Tissue Act (1992)* and with local ethics approval (project ID: 12292). The abductor hallucis muscle and tendon are often affected by first ray deformities and as such the exclusion criteria included any signs of previous surgery, or any obvious deformities of the first ray such as, visual hallux valgus or hallux varus. Specimens were further screened for osteophytic growth and signs of degeneration via in-lab x-ray (see Appendix 5.10) and CT imaging (see Appendix 5.11).

The feet were CT scanned with a Siemens Biograph 128-slice ultraHD-PET CT scanner (Siemens, Germany; see Appendix 5.11) in order to segment bone surfaces for 3D modelling. Skin was removed from the medial aspect of the foot from the base of the first MT to the distal phalanx of the first ray. A medial approach was taken onto the medial surface of the AbH muscle. A fascicular dissection strategy (see Appendix 5.2) was employed to follow along the superficial surface of each structure. Fascicular dissection involved the direct observation of individual tissue fascicles under magnification. Decision-making regarding tissue retention or removal was based on the course of specific fascicles. A surgical microscope (Wild Heerbrugg M651, Switzerland) was used to observe these tissues under 7-36x magnification, as required. Tissues were dissected until fascicles

terminated, either in skeletal attachment, or by converging with other soft tissues. The surface of the AbH muscle and tendon were followed in this fascicular manner, from distal to proximal, to differentiate the AbH tendon from other fascicular structures, including the tendon of the medial head of the FHB muscle. The AbH muscle was then sectioned at its musculo-tendinous junction and the isolated AbH tendon was reflected distally. The same procedure was carried out for the medial head of the FHB muscle. At each level of dissection, attachments to bone were carefully clarified by removing any soft tissue, including periosteum, at the periphery of each attachment “footprint”. If this peripheral tissue was associated with another structure of interest, the border was marked with ink. Each target structure was cut to leave a minimal stump, facilitating direct observation of the complete circumference of the footprint at once. At each stage of dissection, the target tissues were described and photographed (EOS 5D mark III, Canon, Japan).

The abductor hallucis (AbH) footprints on both HS and the proximal phalanx were outlined and modelled into a virtual 3D space using a digital microscribe (Microscribe G2X, ImmersionCorp, USA; see Appendix 5.3). The microscribe recorded the 3D coordinates of a single point into a virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA). A sequence of points located along a surface were converted into a digital line, and a series of digital lines used to render a model of a surface in the virtual environment. Utilising this process for each footprint not only rendered them in 3D, but allowed measurements of each to be taken, inclusive of their

curvature. Footprints were modelled in triplicate to facilitate assessment of the accuracy and reproducibility of the process. Images were reviewed with an expert team including anatomists and clinicians, but the measurements were carried out by the author as a single intra-observer study. The area and perimeter of each footprint was measured in the virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA). To facilitate this process for all relevant attachments, footprints were dissected off once their modelling sequence was complete. This facilitated clear observation, modelling and measurement of subsequent footprints.

The digital models of each footprint were then matched to their respective CT data. These data had been segmented and meshed to create models of the HS, proximal phalanx and first metatarsal. Overlying the bone models with the corresponding footprint models allowed visualisation of the complete array of footprints in three dimensions. The virtual environment software (Rhinoceros 4.0, Robert McNeel and Associates, USA) allowed for area measurements of the non-articular surface of each HS and of each footprint model. Analysis of these data allowed for consideration of each HS attachment as a percentage of the available HS surface area.

To aid 3D visualisation of data, surface scans of relevant skeletal surfaces were created using a laser surface scanner (Artec3D, Luxembourg; see Appendices 5.6-5.9).

To determine the accuracy and reproducibility of the measurements and footprint modelling undertaken, all measurements and footprint models were done in triplicate. The data from each round of measurement/modelling were analysed for statistically significant differences at a standard confidence interval ($p = 0.05$).

3.1.3 Results

The AbH tendon was the first and most apparent interaction of fibrous tissue with the medial aspect of the medial sesamoid. The attachment varied in type, but was found to consistently attach with a bony footprint onto the medial sesamoid. The mean area of the AbH attachment to the medial aspect of the medial sesamoid ($26.01 \pm 6.32 \text{ mm}^2$) was approximately 15% of the non-articular measured surface of the medial sesamoid. Only the deep and plantar parts of the AbH tendon attached to the sesamoid, whereas the more superficial fibres continued distally onto the plantar medial aspect of the medial plantar tubercle of the proximal phalanx. The mean area of the phalangeal attachment ($60.28 \pm 8.42 \text{ mm}^2$) was approximately 25% of the proximal phalanx measured footprint surface (Figures 3.1.1- 3.1.3).

There were two distinct types of AbH morphologies: type A (n= 18, 56%) where the AbH seemingly enveloped the medial aspect of the medial sesamoid and attached with a single large footprint ($27.74 \pm 6.7 \text{ mm}^2$) dorsally on the proximal third of the medial aspect of the medial sesamoid with some plantar oriented fibres plantarly (Figure 3.1.2). Type B was less common (n=14, 44%) and had a similar main footprint dorsally on the proximal third, but with a smaller footprint ($13.22 \pm 1.22 \text{ mm}^2$) and a distinct plantar set of fascicles that curved to a nearly dorso-plantar orientation, to attach onto the more plantar proximal third of the medial sesamoid, with a smaller footprint ($9.12 \pm 0.80 \text{ mm}^2$; Figure 3.1.3).

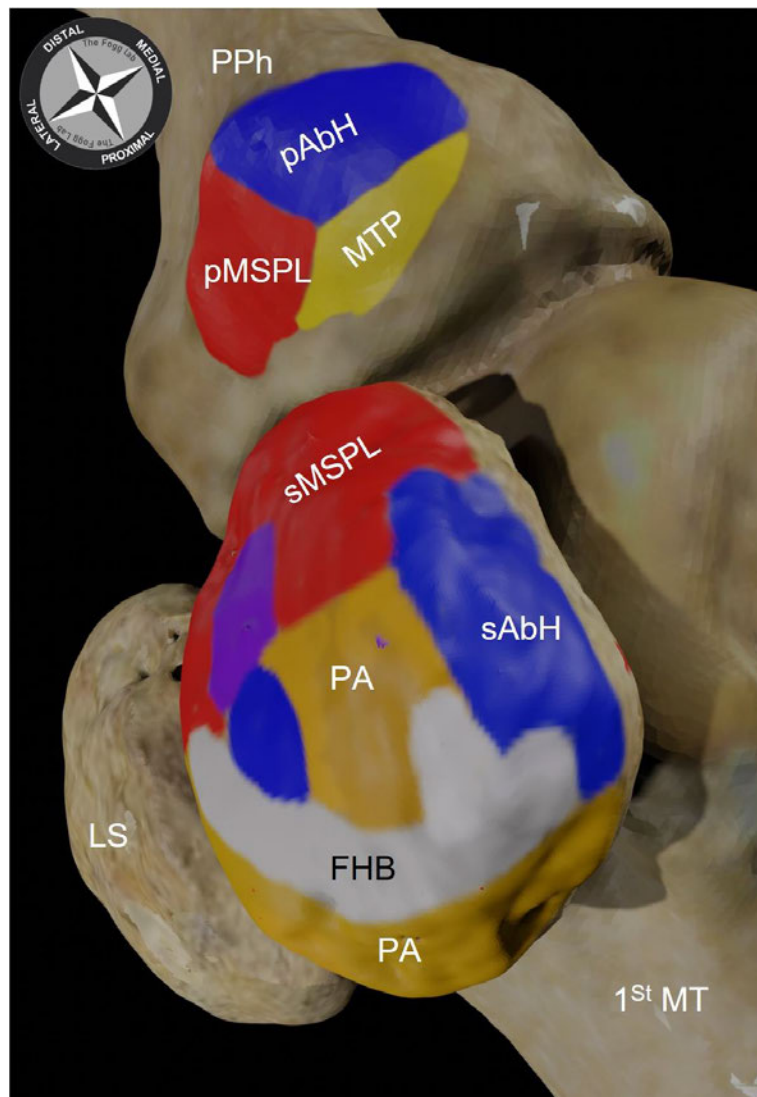


Figure 3.1.1. A plantar medial view of a 3D reconstruction of an osseous first metatarsophalangeal joint, highlighting the attachment areas on the medial sesamoid and medial tubercle of the proximal phalanx (PPh). The abductor hallucis footprints of a type B abductor hallucis on the sesamoid (sAbH, blue) are seen on the dorsal medial aspect of the medial sesamoid, with a phalangeal footprint (pAbH, blue) distally on the medial aspect of the medial plantar tubercle of the PPh. The AbH footprints were closely associated with the footprints of the plantar aponeurosis (PA, orange) the flexor hallucis brevis (FHB, white) as well as the sesamophalangeal ligament both on the sesamoid (sMSPL, red) and on the PPh (pMSPL, red), additionally on the capsular aspect on the PPh the metatarsophalangeal ligament was found to attach proximal to the pAbH. Dorsal to the sAbH footprint was the medial metatarsosesamoid ligament and its footprint .LS; lateral sesamoid.



Figure 3.1.2. A medial view of a right foot with the first metatarsal (1st MT) and proximal phalanx (PPh) dissected to the bone with the medial collateral ligament exposed (black lines). A type A abductor hallucis tendon (AbH, blue lines) approached and enveloped the dorsal half of the medial aspect of the medial sesamoid (MS) and the visible superficial fibres continued distally, where some turned dorsally to merge with the extensor hood (dashed blue lines). Plantarly, the flexor hallucis brevis (FHB) tendon contributed fibres to the plantar-most aspect of the AbH tendon.

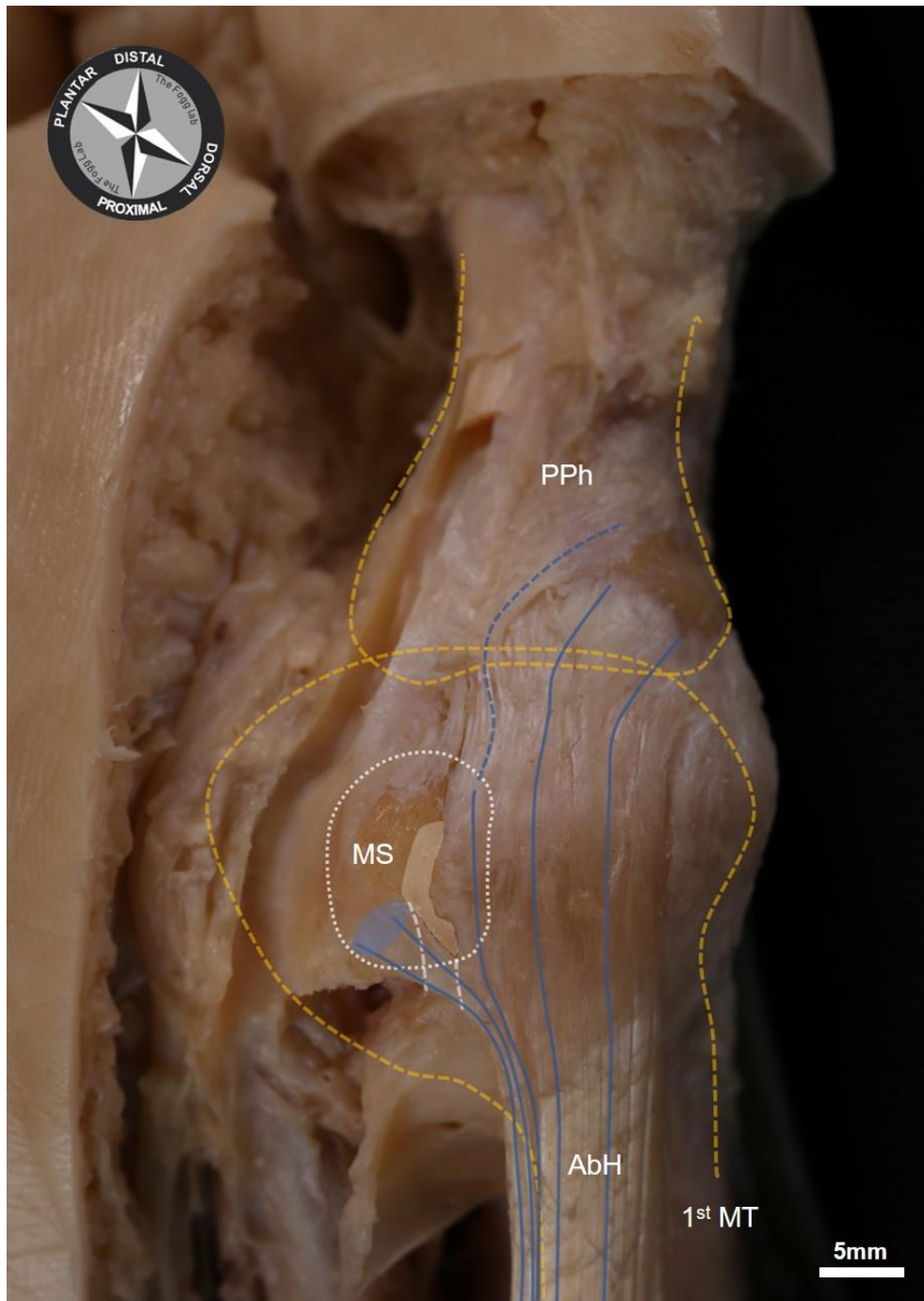


Figure 3.1.3. A plantar medial view of a right foot with the first metatarsal (1st MT) and proximal phalanx (PPh) dissected to fibrous tissues. A type B abductor hallucis (AbH, blue lines) tendon approached and enveloped the dorsal third of the medial aspect of the medial sesamoid (MS), giving off some plantar-directed fibres as a slip that attached onto the more plantar aspect of the MS (blue shadow). A few of the superficial fibres continued distally, where some turned dorsally to merge with the extensor hood (dashed blue lines). Plantarly, the flexor hallucis brevis (removed) ran beneath the AbH slip (white dashed lines) and attached onto the MS (white shadow).

In multiple specimens (n=2, 6%) the AbH had small sets of fibres interacting with the flexor hallucis longus tunnel distally on the proximal phalanx.

At the level of the medial sesamoid the deeper and more plantar AbH tendon fibres were not independent, as they were joined in all specimens (n=32; 100%) by medial components of the medial FHB tendon (Figures 3.1.2 - 3.1.4). The interdigitating fibres of the medial FHB tendons were thin and negligible compared to the size of the AbH fibres.

As discussed previously (see Part One, Chapter Three), the distal pole of the medial sesamoid was the site of attachment of the medial sesamophalangeal ligament. The longitudinal fibres ran in the same direction as those of the overlying AbH distal tendon and were adherent; these could only be separated with careful fascicular dissection. These two sets of fibres remained contiguous up to their attachments on the medial plantar tubercle of the proximal phalanx (Figure 3.1.3).

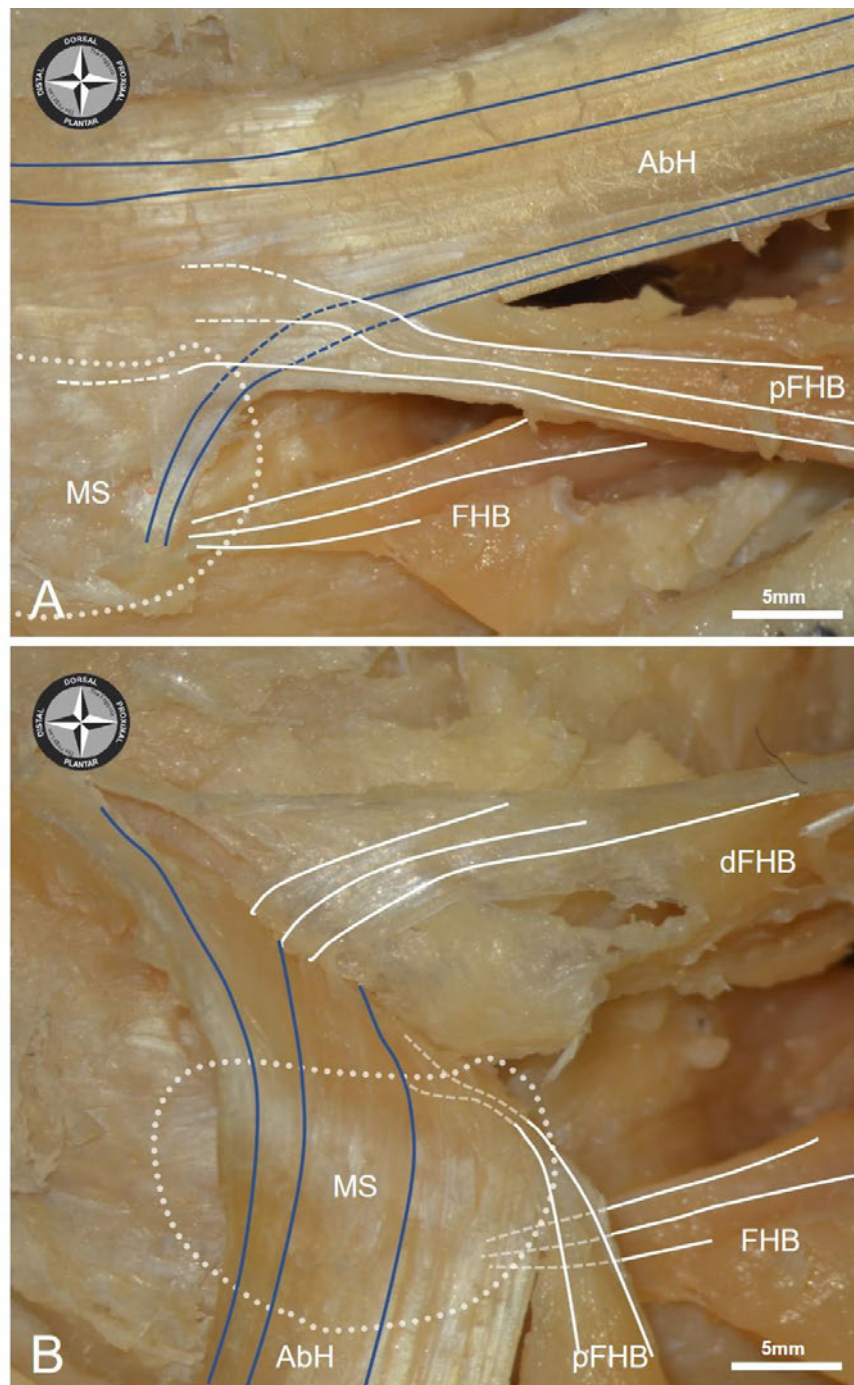


Figure 3.1.4. The interdigitations of the flexor hallucis brevis (FHB, white lines) into the abductor hallucis (AbH, blue lines) tendon. A - Medial view of a right first metatarsophalangeal joint proximal to the medial sesamoid (MS, white dotted line), with a type B AbH tendon being interdigitated plantarly by a component of the FHB (pFHB). B - The same medial view with the AbH reflected plantarly (blue lines) showing its deep surface, highlighting the merging of thin FHB (dFHB) fibres. In both A and B there was a direct FHB attachment to the proximal plantar aspect of the MS.

In a small number of specimens (n=2, 6%), a small set of fibres were identified to run further plantarly to contribute to the dorsal roof of the flexor hallucis longus tunnel. At the level of the medial sesamoid, on the distal and dorsal aspect of the AbH tendon, a set of fibres was consistently observed that had previously not been reported; these fibres will be addressed in a later chapter (see Part 2, Chapter 5).

The summary of these findings is as follows: The Abh tendon consistently attached onto the MS with a relatively large bony footprint, and continuing distally to attach onto the medial plantar tubercle of the PPh. The AbH had two distinct morphologies, with differing attachment patterns to the MS, with the occasional communication into the flexor hallucis longus tunnel. The AbH was consistently contributed to by a small proportion of the medial fibres of the FHB tendon. Deep to the AbH tendon between the MS and the PPh the adherent fibres of the medial SPL were consistently identified, bordering the distal PPh attachment of the AbH.

3.1.4 Discussion

The distal attachment sites of the main AbH tendon observed within the current study confirm previous work, identifying the medial sesamoid and the plantar base of the proximal phalanx as the distal attachment sites (Agawany *et al.*, 2010; Brenner, 1999; Theumann *et al.*, 2002). Within these previous studies the AbH tendons attached to the proximal phalanx alone in parts of their sample, bypassing the medial sesamoid (Agawany *et al.*, 2010; Brenner, 1999). The current work identified a footprint of the AbH tendon to the medial sesamoid in all specimens (n=32, 100%). Attachment of deep fibres of the tendon had previously been described as to the “medial sesamoid ligament” (Brenner, 1999), referencing fan-shaped fibres reinforcing the medial aspect of the first MTPJ capsule from the dorsal aspect of the medial sesamoid to the medial aspect of the metatarsal head. This description suggests that it was the medial metatarsosesamoid suspensory ligament (Schneider, 2013); Figure 3.1.2). This connection of deep fibres to the metatarsosesamoid suspensory ligament may have also extended to the medial sesamoid plantarly if dissected in a fascicular manner. Additional types described by previous work include a single attachment point to the medial sesamoid alone (Agawany *et al.*, 2010; Brenner, 1999). Despite this typing, it was also stated that the fibres continued distally to spread onto the medial border of the proximal phalanx (Agawany *et al.*, 2010; Brenner, 1999). This suggests a distal attachment onto the proximal phalanx to the proximal attachment onto the medial sesamoid, more in line with the consistent

observation of a proximal phalangeal attachment in the current study (n=32, 100%; Figure 3.1.1).

Most previous work on the AbH tendon identified that the medial FHB interacted with the AbH tendon in a meaningful way, reaching the distal attachment points at the medial sesamoid (Wong, 2007) and proximal phalanx together (Agawany *et al.*, 2010; Brenner, 1999). This was confirmed in the current study, with deep and plantar interdigitations from the FHB identified (Figure 3.1.4). The identified interdigitating medial FHB tendons joined larger, more organised AbH fibres, and so were not likely major functional contributors. Further research into the functional roles of the interdigitations is required.

Damage to the FHB has been shown to result in cock-up toe deformity (Coughlin *et al.*, 2013). The identification of the interdigitating fibres between the medial head of the FHB and the AbH tendon suggests that targeting the AbH tendon distally would functionally affect the medial head of the FHB and may lead to iatrogenic cock-up toe deformity (Bartosiak *et al.*, 2019; Coughlin *et al.*, 2013). A more proximal AbH tenotomy proximal to the main FHB interdigitations may prevent such complications. Additionally, during medial capsulorrhaphy in hallux valgus correction, damage to the distal AbH tendon contiguous with the first MTPJ capsule would cause an “imbalance” to the forces acting on the first MTPJ (Coughlin *et al.*, 2013; Schneider, 2013). Abduction forces may be limited due to functional losses of the AbH and part of the medial FHB, leaving the hallux open to progressive valgus, leading to

recurrence of the deformity. Damage to the AbH, if carried out during hallux valgus correction surgery alongside a lateral soft tissue release leaves the first MTPJ unstable, and liable to functional loss and hallux varus (Coughlin *et al.*, 2013).

The inconsistency of the previously reported interactions of the AbH tendon onto the medial sesamoid, the proximal phalanx and the medial aspect of the first MTPJ capsule may in part be due to inconsistencies in methodologies (Agawany *et al.*, 2010; Brenner, 1999; Mitchell, 1980; Theumann *et al.*, 2002). The defining difference between the current study and previous work was the fascicular dissection method; using consistent methods and a defined set of rules may help to achieve consistent results and may increase reproducibility of results, supporting easier and clearer comparison between studies.

This research was not without limitations. The Donors studied came from a sample population with a high mean age (81.3 years), which may suggest that the small structures studied to be smaller, thinner and/or weaker. The consistent findings of the current data suggest this was not an issue, but comparisons with a younger sample population would be welcomed. In this study intra-observer variation was assessed, future studies can include interobserver observation on key findings. The combined dissection and digital modelling approach facilitated the detailed assessment of the AbH attachments in three dimensions and allowed for a reconstructive approach to visualising dissection data. Despite these advantages, the

dissection process remains destructive. Future studies could include sectional analysis (macro-sections, histology, diceCT, etc.) to observe tissue interrelations with less investigative disruptions. Comparison data from these approaches would provide a more comprehensive account of the detailed anatomy. Biomechanical studies of the relative strengths of the AbH footprints and tendon proximal and distal to the medial sesamoid would clarify which attachment is most crucial in force transmission to the hallux.

The AbH distal attachments have been clearly defined with close relations to active and passive elements of the first ray complex. These data will contribute to improved anatomical understanding of this complex, which will inform continued improvements in the clinical management of conditions such as medial capsulorrhaphy and abductor tenotomies such as in recurrent clubfoot and hallux varus deformities.

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Part Three, Chapter Two

3.2 Superficial Medial Collateral Ligament

3.2.1 Introduction

The medial aspect of the first metatarsophalangeal (MTPJ) has a potential set of interactions between the incoming tendons of the flexor hallucis brevis (FHB) medial head (Pinto *et al.*, 2010), the abductor hallucis (AbH), as well as passive structures, such as the medial collateral ligament, the medial capsule, and a slip from the first bundle of the plantar aponeurosis (PA) (Kelikian *et al.*, 2011). The medial aspect of the medial sesamoid (MS) is clinically important due to these attachments, such as the AbH distal tendon at the level of the medial sesamoid, which is targeted in recurrent clubfoot deformity (Fadel, 2019), AbH tendon transfer (Hawkins, 1971) and released as part of metatarsus varus correction (Mitchell, 1980). Additionally, the MS may have a role in the pathomechanism of conditions such as hallux valgus, where the restraints to the medial aspect of the MS were important in resisting the gradual lateral subluxation of the sesamoid complex relative to the first metatarsal head. The literature stated that the soft tissues on the medial aspect of the first MTPJ became attenuated as hallux valgus progressed (Coughlin *et al.*, 2013). Therefore, within many hallux valgus correction surgeries, the medial capsule is reefed or imbricated with a medial capsulorrhaphy at the level of the MS (Coughlin *et al.*, 2005; Kitaoka *et al.*, 1991; Quill Jr, 2005; Wuelker, 1994).

The soft tissues on the medial aspect of the first MTPJ were not well described within the literature. The principles components were suggested to be the medial collateral ligament, the medial sesamoid ligament, and the joint capsule (Smyth *et al.*, 2018). The collateral ligament was subdivided into two separate structures, the metatarsophalangeal ligament which connects the first metatarsal head with the proximal phalanx in an plantar-distal fibre direction (Kelikian *et al.*, 2011; Richardson, 1987), and the metatarsosesamoid ligament, or metatarsosesamoid suspensory ligament, which connected the medial margin of the MS or plantar plate (PP) to the medial tubercle on the first metatarsal head (Dedmond *et al.*, 2006; Lin *et al.*, 1996; Pinto *et al.*, 2010; Schneider, 2013). The metatarsosesamoid ligament was said to be essential for maintaining the position of the hallucal sesamoids and PP relative to the first metatarsal head (Boike *et al.*, 2011; Nery *et al.*, 2017). The medial sesamoid ligament (Smyth *et al.*, 2018), elsewhere described as a fan-shaped set of fibres reinforcing the medial capsule of the first MTPJ and attaching the MS to the medial aspect of the first metatarsal head (Brenner, 1999), was in line with other descriptions of the sesamoid ligament (Dedmond *et al.*, 2006; Haines *et al.*, 1954; Pinto *et al.*, 2010). This description was also the same as that for the metatarsosesamoid ligament portion of the medial collateral ligament. The structure and naming of these medial soft tissues were ambiguous throughout the literature and the various components have been named and described inconsistently. Most commonly, the medial metatarsosesamoid ligament is often confused for the medial sesamoid ligament and *vice versa* (Boike *et al.*, 2011; Brenner, 1999; Dedmond *et al.*, 2006; Haines *et al.*, 1954;

Leventen, 1991; McCormick *et al.*, 2010; Pinto *et al.*, 2010; Richardson, 1987; Richardson, 1999).

The MS and its relationships have been an area of interest, with papers identifying many interacting structures, and their variations of attachment. Attachments such as the AbH (Agawany *et al.*, 2010; Brenner, 1999; Wong, 2007), the FHB (Richardson, 1987; Wong, 2007) the plantar aponeurosis (Do Carmo *et al.*, 2008; Hedrick, 1996), and the medial collateral ligament (Kelikian *et al.*, 2011; Richardson, 1987; Schneider, 2013) have been variously described attaching to the MS. Despite all this research there is one structure on the medial aspect of the MS which was not described in the reviewed literature, the superficial medial collateral ligament (SMCL).

This work will describe the course and map the attachments of the SMCL to glean a potential functional role for this novel structure.

3.2.2 Material and Methods

Feet from embalmed (Genelyn Anatomical Series, Australia; see Appendix 5.1) Body Donors (n = 32; female =15, Male = 17; mean age = 81.3 years) were examined in accordance with *Part IV of the Human Tissue Act (1992)* and with local ethics approval (project ID: 12292). The position of the superficial medial collateral ligament on the medial aspect of the first MTPJ puts it at risk of being affected during first ray deformities, as such exclusion criteria included any signs of previous surgery, or any obvious deformities at the first ray such as, visual hallux valgus, hallux varus, and if during dissection gout or signs of joint degeneration were observed.

The feet were CT scanned with a Siemens Biograph 128-slice ultraHD-PET CT scanner (Siemens, Germany; see Appendix 5.11) in order to segment bone surfaces for 3D modelling. Skin was removed from the medial aspect of the foot from the base of the first MT to the distal phalanx of the first ray. A medial approach was taken onto the medial surface of the AbH muscle. A fascicular dissection strategy (see Appendix 5.2) was employed to follow along the superficial surface of the AbH medial surface until distally reaching the medial sesamoid at which point any overlying fibres running plantar to dorsal were carefully dissected out in a fascicular manner following individual fascicles to their attachments plantarly and dorsally. Fascicular dissection involved the direct observation of individual tissue fascicles under magnification. Decision-making regarding tissue retention or removal was based on the course of specific fascicles. A surgical microscope (Wild Heerbrugg M651, Switzerland) was used to observe these tissues under 7-

36x magnification, as required. Tissues were dissected until fascicles terminated, either in skeletal attachment, or by converging with other soft tissues.

At each level of dissection, attachments to bone were carefully clarified by removing any soft tissue, including periosteum, at the periphery of each attachment “footprint”. If this peripheral tissue was associated with another structure of interest, the border was marked with ink. The target structure was cut to leave a minimal stump, facilitating direct observation of the complete circumference of the footprint at once. At each stage of dissection, the target tissue was described and photographed (EOS 5D mark III, Canon, Japan).

The Superficial medial collateral ligament (SMCL) footprints of skeletal attachments were outlined and modelled into a virtual 3D space using a digital microscribe (Microscribe G2X, ImmersionCorp, USA; see Appendix 5.3). The microscribe recorded the 3D coordinates of a single point into a virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA). A sequence of points located along a surface were converted into a digital line, and a series of digital lines used to render a model of a surface in the virtual environment. Utilising this process for each footprint not only rendered them in 3D, but allowed measurements of each to be taken, inclusive of their curvature. Footprints were modelled in triplicate to facilitate assessment of the accuracy and reproducibility of the process. The area and perimeter of the footprint was measured in the virtual environment (Rhinoceros 4.0,

Robert McNeel and Associates, USA). To facilitate this process for the attachments, they were dissected off once their modelling sequence was complete. This facilitated clear observation, modelling and measurement of subsequent footprints.

The digital models of each footprint were then matched to their respective CT data. These data had been segmented and meshed to create models of the HS, proximal phalanx and first metatarsal. Overlying the bone models with the corresponding footprint models allowed visualisation of the complete array of footprints in three dimensions. The virtual environment software (Rhinoceros 4.0, Robert McNeel and Associates, USA) allowed for area measurements of the non-articular surface of each hallucal sesamoid and of each footprint model. Analysis of these data allowed for consideration of each HS attachment as a percentage of the available hallucal sesamoid surface area. To aid 3D visualisation of data, surface scans of relevant skeletal surfaces were created using a laser surface scanner (Artec3D, Luxembourg; see Appendices 5.6-5.9).

To determine the accuracy and reproducibility of the measurements and footprint modelling undertaken, all measurements and footprint models were done in triplicate. These measurements were done by the author as a single intra-observer study, with select measures and images interpreted by senior clinicians and anatomist. The data from each round of measurement/modelling were analysed for statistically significant differences at a standard confidence interval ($p = 0.05$).

3.2.3 Results

Superficial to the tendino-ligamentous structures around the MTPJ, a ligament was consistently identified (n=21, 100%) on the middle third of the medial aspect of the MS. The MS footprint (mean area = $16.08 \pm 6.26 \text{ mm}^2$) occupied approximately 10% of the non-articular measured surface of the MS (Figure 3.2.1). This attachment onto the MS was robust; the SMCL ligament then coursed dorsal-distal in all specimens.

The dorsal course of the SMCL varied between Body Donors with three distinct types observed: type I was the most common type (n=20, 62%) and had a course that fanned dorsally into multiple separate fragile fascicles and interdigitated within layers of the AbH distal tendon, interdigitating superficially and deep (Figure 3.2.2); type II was quite common (n= 9, 28%) and similar to type I, but the fascicles were closer to parallel along their course, thicker, and interdigitated with the AbH dorso-distally (Figure 3.2.3); type III was the rarest type of SMCL (n=3, 9%), where the fibres were more organised and considerably thicker than types I and II, and coursed dorsal-distal, superficial to the AbH distal tendon, to merge into tissues dorsomedial on the proximal phalanx (Figure 3.2.4).

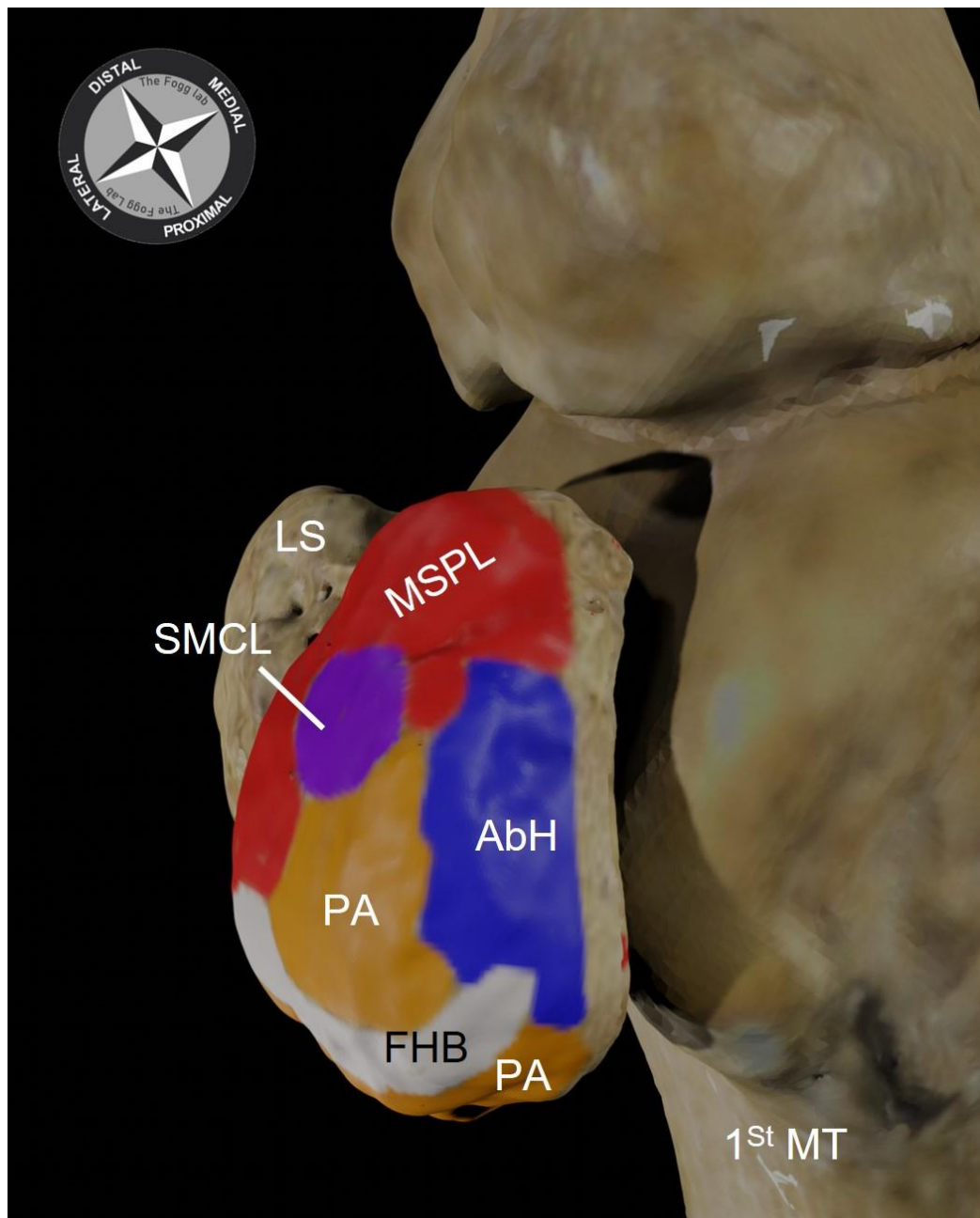


Figure 3.2.1. A medial view of a 3D reconstruction of an osseous first metatarsophalangeal joint, highlighting attachment areas on the medial sesamoid and medial tubercle of the proximal phalanx (PPh). The superficial medial collateral ligament footprint is seen attaching with a relatively large surface area (SMCL, purple) on the middle third of the medial sesamoid. The SMCL footprint was closely associated with the footprints of the plantar aponeurosis (PA, orange) and the medial sesamophalangeal ligament (MSPL, red), occasionally the footprint adjoined the abductor hallucis footprint (AbH, blue). LS: lateral sesamoid, FHB: flexor hallucis brevis.

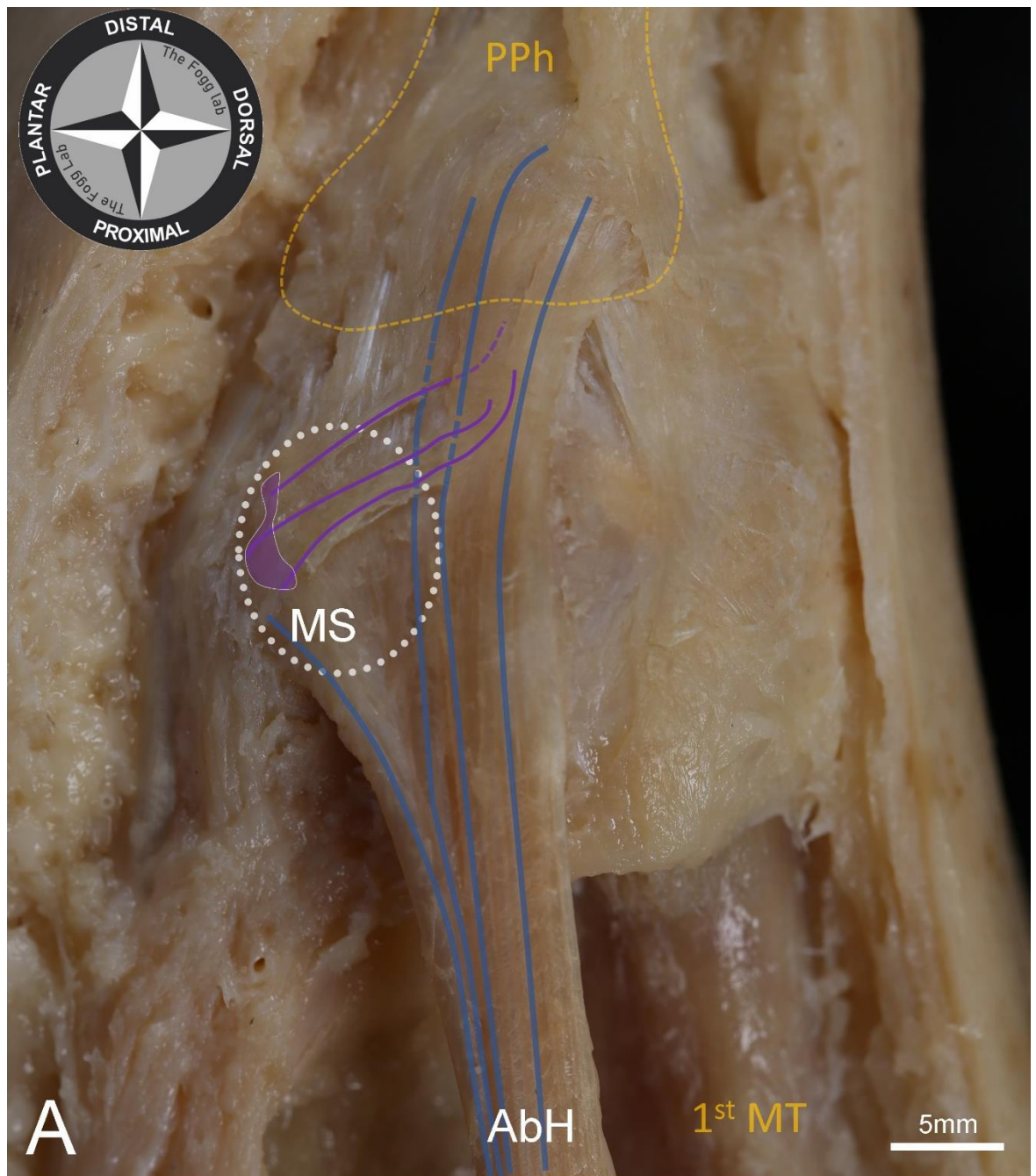


Figure 3.2.2. Medial view of a right first metatarsophalangeal joint with a type I superficial medial collateral ligament (purple lines) with a footprint (purple shadow) onto the medial sesamoid (MS, white dotted line), and interdigitating dorsal-distal with the abductor hallucis (AbH), blue lines) attaching in a type A manner to the sesamoid and to the proximal phalanx (PPh) distally, whilst overlying the first metatarsal (1st MT).

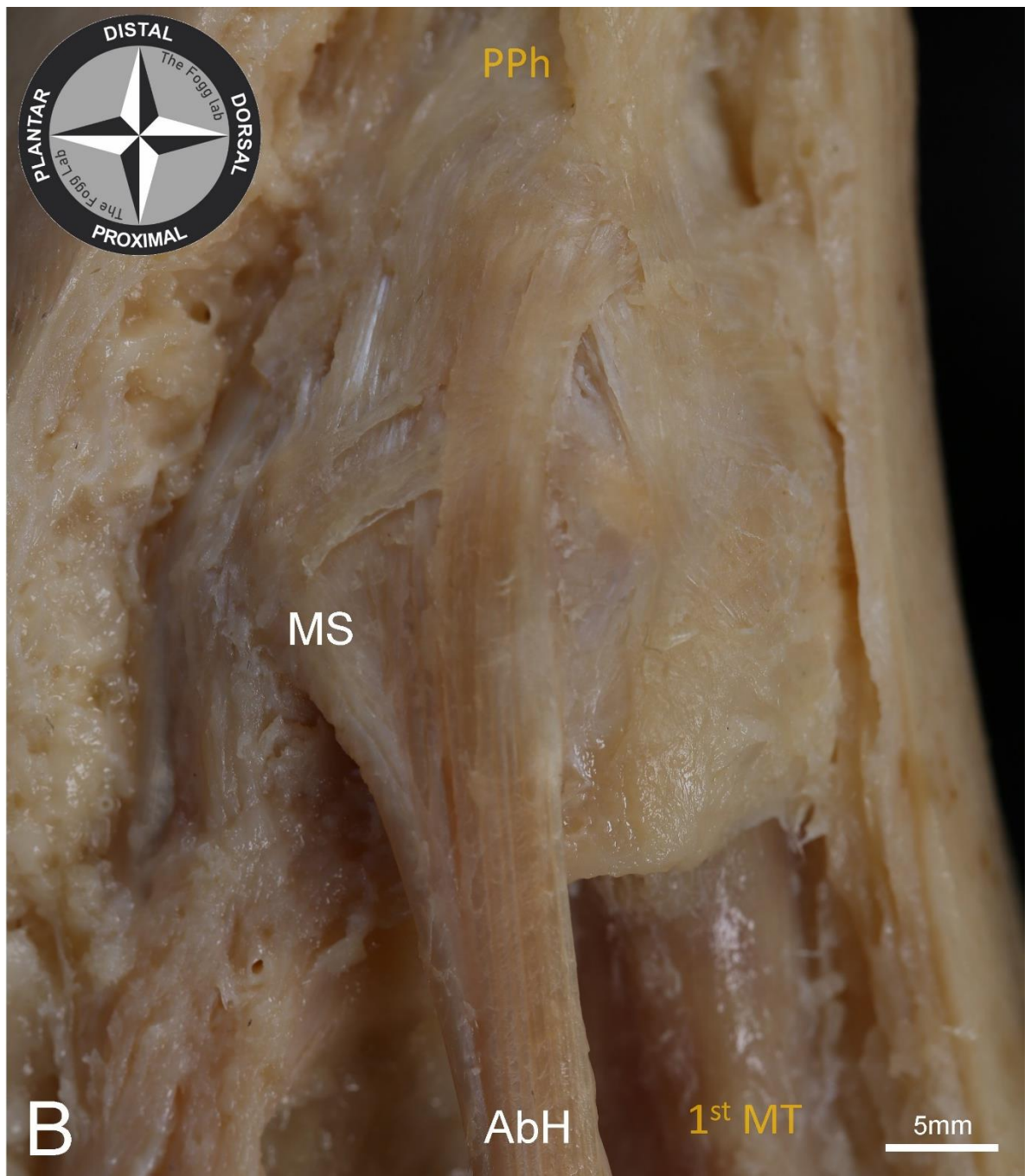


Figure 3.2.2. *continued*. B- A non-annotated view of A.

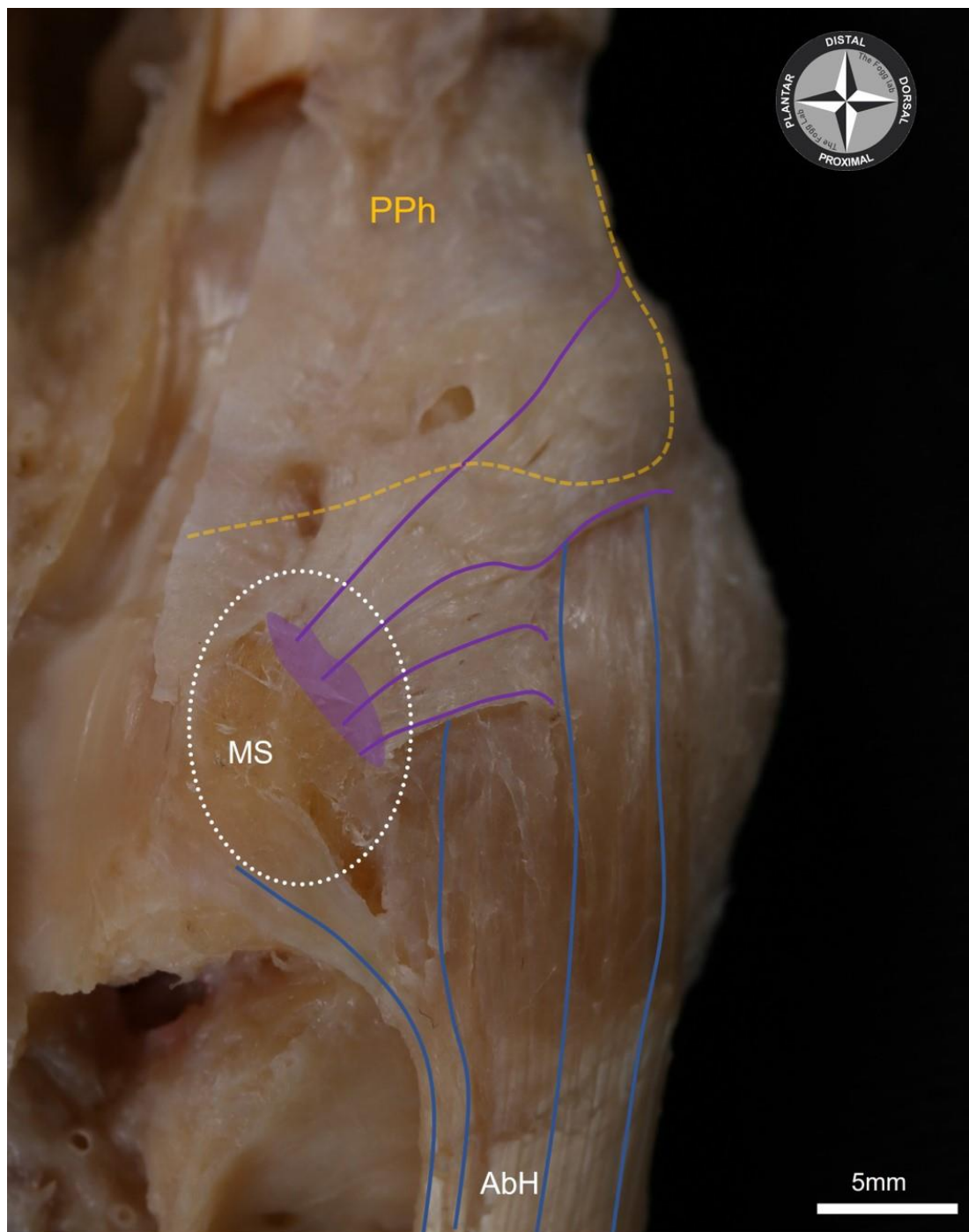


Figure 3.2.3. Medial view of a right first metatarsophalangeal joint with a type II superficial medial collateral ligament (purple lines) with a footprint (purple shadow) onto the medial sesamoid (MS, white dotted line), and interdigitating dorsal-distal with a type B abductor hallucis (AbH, blue lines) and with some of its more dorsal fibres overlying the proximal phalanx (PPh)

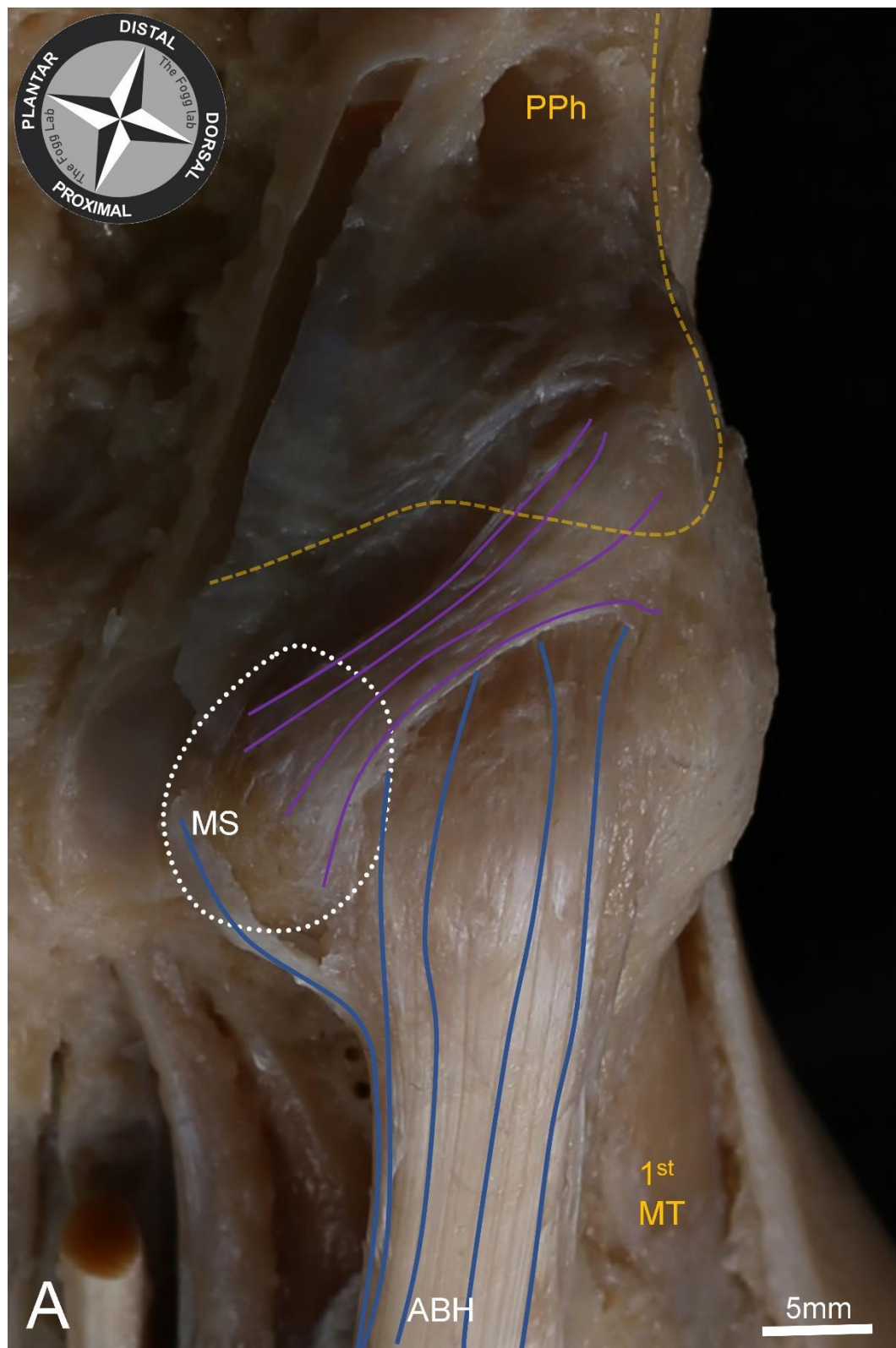


Figure 3.2.4. Medial view of a right first metatarsophalangeal joint with a type III superficial medial collateral ligament (purple lines) with a footprint onto the medial sesamoid (MS, white dotted line), and interdigitating dorsal-distal with extensor aponeurosis tissues.



Figure 3.2.4. *continued*. B- A non-annotated view of A.

The SMCL was found to connect with superficial fibres of the FHB in a limited number of specimens (n=2, 6.25%). In these cases, only a fraction of the fibres from the FHB connected to the SMCL as it coursed dorso-distal. This only occurred in type I feet (Figure 3.2.5).

In Summary the SMCL was identified in all specimens on the middle third of the medial aspect of the MS with a robust attachment to the MS reaching dorso-distally to the dorso medial tissues of the PPh with three distinct morphologies. On a few occasions the SMCL communicated with the tendon of medial head of the FHB.

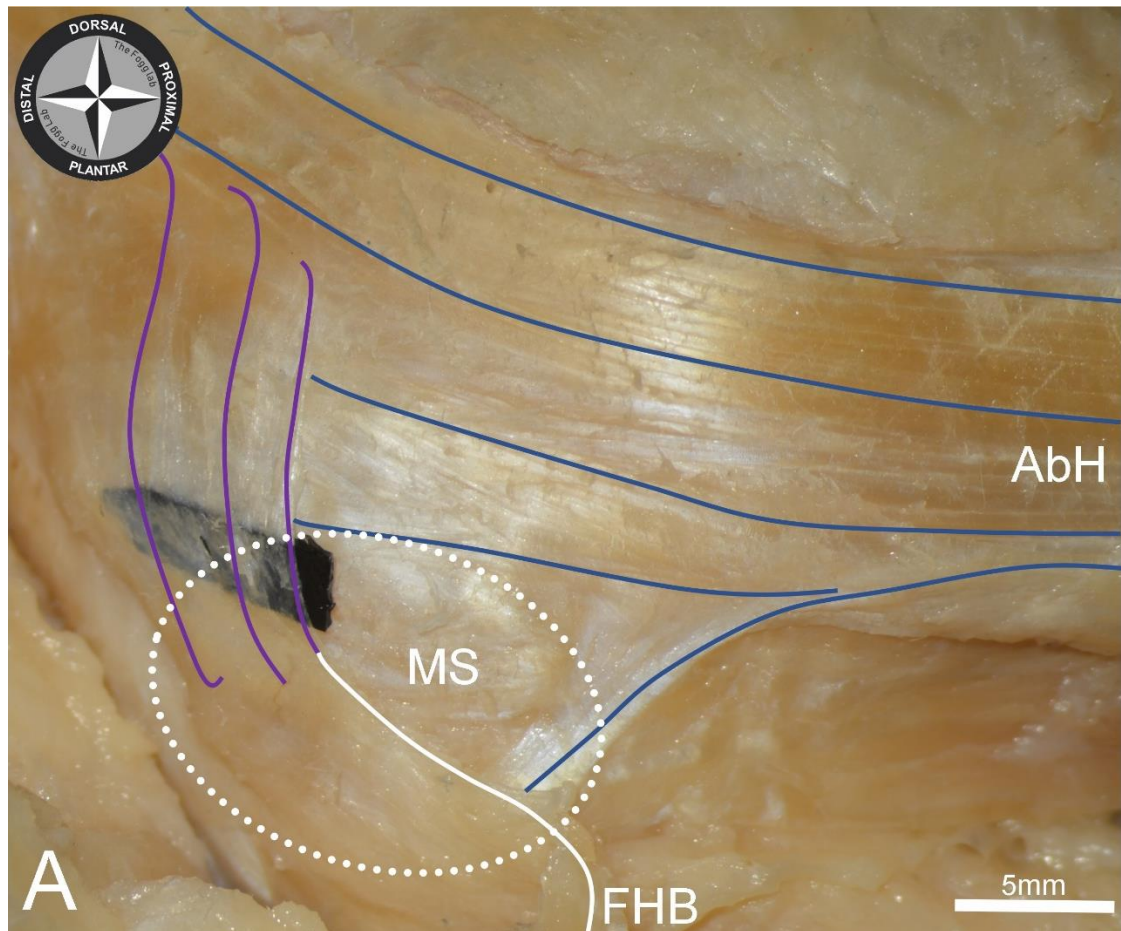


Figure 3.2.5. Medial view of the first metatarsophalangeal joint at the level of the medial sesamoid (MS, white dotted line), highlighting the unusual set of fibres from a plantar-medial set of flexor hallucis brevis (FHB, white line) contributing to the proximal most fibres of the type I superficial medial collateral ligament (purple lines) as it interdigitates with the fibres of the abductor hallucis (AbH, blue lines).

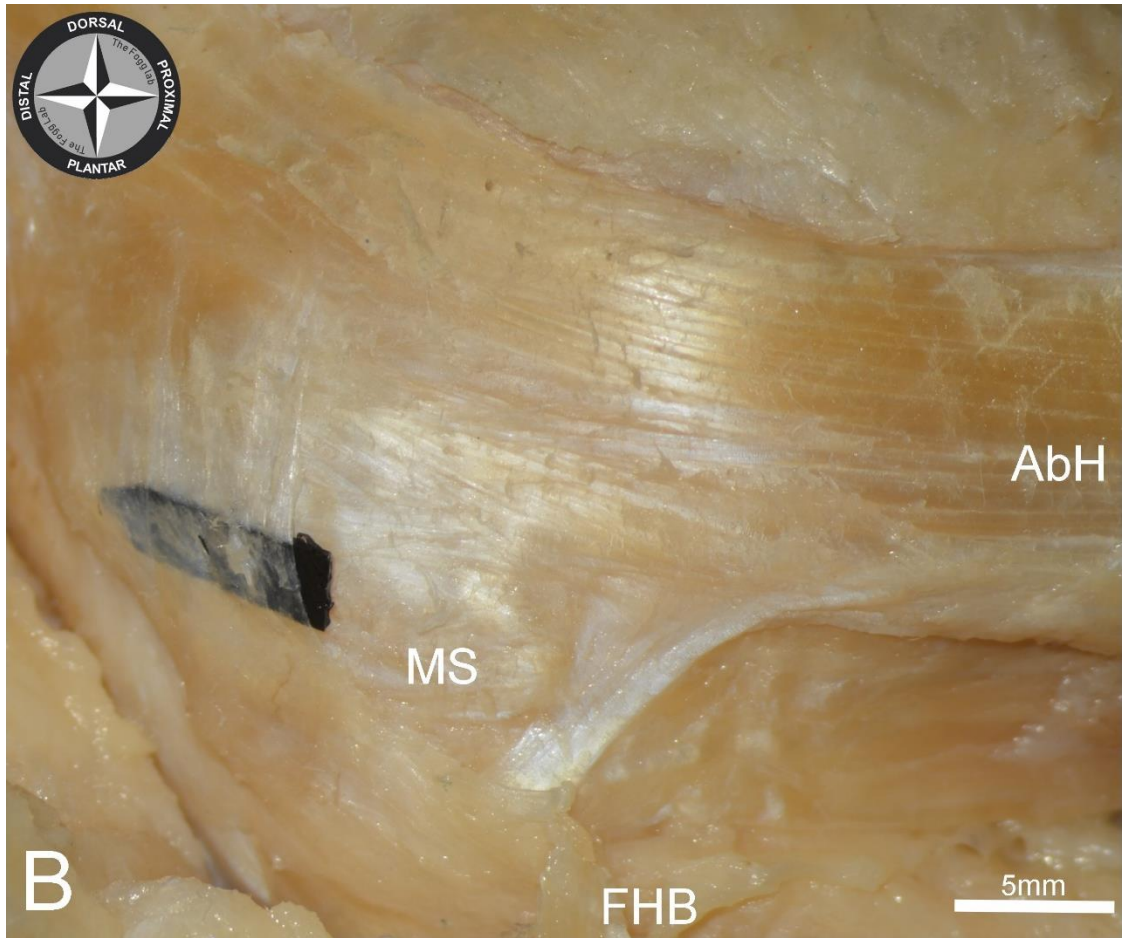


Figure 3.2.5. *continued*. B- A non-annotated view of A.

3.2.4 Discussion

Early on in the study only type I and type II SMCL had been identified, and were considered to perhaps be an unusual course of the AbH distal tendon fibres attaching onto the medial sesamoid. However with the identification of type III, with thicker, more organised fibres running superficial and distal to the entirety of the distal AbH tendon onto the medial aspect of the proximal phalanx, the SMCL took on a more substantial potential role. The position and morphology of the type III SMCL suggests a stabilising role for the MS and first MTPJ complex, restraining the hallucal sesamoidal apparatus from lateral deviation relative to the first metatarsal head and proximal phalanx during the progression of hallux valgus. This position makes it likely to be one of the medial soft tissues that are attenuated during hallux valgus (Smyth *et al.*, 2018). The SMCL was distinct from the medial metatarsosesamoid ligament as it lied superficial to the AbH tendon, and traveled to the AbH tendon and PPh, and not the first metatarsal head. The SMCL was distinct from the metatarsophalangeal ligament because of the superficial nature of the SMCL and that their respective fibres run orthogonal to each other. The reviewed literature contained no mention of fibres similar to those described as the SMCL, suggesting that these fibres were a novel finding.

The intimate relationship of the SMCL on the superficial surface of the AbH highlights the link between the MS and the AbH tendon more than previously thought, the SMCL represents a fascicular connection between

the AbH tendon and the MS, especially in types I and II. Suggesting, that even in reports where the AbH does not attach onto the medial sesamoid (Agawany *et al.*, 2010; Brenner, 1999), there is a connection between the two.

The dorsal-medial fibres of the AbH have been identified to interact with the plantar-medial extension of the extensor hood (Charpy *et al.*, 1901; Pfeffer *et al.*, 2017). Additionally, the deep fibres of the AbH tendon, as well as those of the extensor aponeurosis, have been identified to attach firmly to the medial aspect of the first MTPJ capsule (Agawany *et al.*, 2010; Brenner, 1999; De Maeseneer *et al.*, 2018; Theumann *et al.*, 2002; Valvo *et al.*, 1987). The MS was also said to be an attachment point for the extensor aponeurosis (Alvarez *et al.*, 1984; Theumann *et al.*, 2002). All of these interactions suggest that the SMCL is the missing link connecting the MS to the AbH tendon (types I and II) and the extensor aponeurosis (type III).

The contiguous nature of the SMCL, superficial to and interdigitating with the distal AbH tendon, theorises that damage to the distal AbH tendon through pathology or tagging in surgical procedures (Coughlin *et al.*, 2005; Fadel, 2019; Hawkins, 1971; Kitaoka *et al.*, 1991; Mitchell, 1980; Quill Jr, 2005; Wuelker, 1994) would cause disruption to the SMCL of all types. Such disruption of the SMCL may reduce the medial stability of the first MTPJ and reduce the overall resistive strength of the medial soft tissue structures anchoring the MS plantar to the first metatarsal head.

This research was not without limitations. Whilst there is no current explanation for the different types of SMCL observed in the current study, the theories are: an age or pathology related degenerative difference, an genetic anatomic variation, or a functionally driven change. The Donors studied came from a sample population with a high mean age (81.3 years), which may suggest that the fascicles of the SMCL may be smaller, thinner and/or weaker, such as the differences between type III with thick and organised fascicles and type I, with thin and fanning fascicles. The SMCL was, however, consistently identified in all specimens (n=32, 100%) and was never fully degenerated or absent. Additional comparisons can be made with the study of the SMCL in populations suffering from forefoot disorders such as hallux valgus, to verify if type III is less common in hallux valgus. The combined dissection and digital modelling approach facilitated the detailed assessment of the SMCL in three dimensions and allowed for a reconstructive approach to visualising dissection data. Despite these advantages, the dissection process remains destructive. Future studies could include sectional analysis (macro-sections, histology, diceCT, etc.) to observe tissue interrelations with less investigative disruptions. Comparison data from these approaches would provide a more comprehensive account of the detailed anatomy. Biomechanical studies of the relative strengths of the SMCL types would clarify their role in resisting lateral subluxation of the medial sesamoid relative to the first metatarsal head. Within this study, only intra-observer variation was assessed, future studies may also include interobserver observation on key findings.

The superficial medial collateral ligament is a novel finding that has been clearly defined as a distinct structure with close relations to active and passive elements of the first ray complex. These data will contribute to improved anatomical understanding of this complex, which will inform continued improvements in the clinical management of conditions affecting the medial soft tissues of the first MTPJ such as hallux valgus.

3.2.5 References

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Part Three, Chapter Three

3.3 Flexor Hallucis Brevis

3.3.1 Introduction

The most cited interaction that the hallucal sesamoids (HS) have with any muscle was with the flexor hallucis brevis (FHB) (Agawany *et al.*, 2010; Arakawa *et al.*, 2003; Athanasiou *et al.*, 1998; Brenner, 1999; de Britto, 1982; Dedmond *et al.*, 2006; Feldman *et al.*, 1970; Inge *et al.*, 1933; Jahss, 1981; Kelikian *et al.*, 2011; Lucas *et al.*, 2014; Richardson, 1999; Van Hal *et al.*, 1982). The tendon of the lateral head of the FHB was said to interact with the lateral sesamoid (LS) and the tendon of the medial head of the FHB with the medial sesamoid (MS), a relationship that was widely accepted (Kelikian *et al.*, 2011). However, authors diverged in opinion on the nature of the interaction. The most common description of the HS in relation to the FHB was that the HS were embedded within the respective tendons of the FHB (Anwar *et al.*, 2005; Athanasiou *et al.*, 1998; Dedmond *et al.*, 2006; Feldman *et al.*, 1970; Inge *et al.*, 1933; Jahss, 1981; Lucas *et al.*, 2014; Powers, 1934; Richardson, 1999; Scranton *et al.*, 1980; Van Hal *et al.*, 1982; York *et al.*, 2017), which continued distally to attach onto the medial and lateral plantar tubercles of the proximal phalanx respectively (Nery *et al.*, 2017; Orr, 1918). As previous work has shown, there are other structures attaching into the HS (Agawany *et al.*, 2010; Brenner, 1999; Lin *et al.*, 1996; Owens *et al.*, 2001), making the description of HS embedded in the FHB tendon heads a simplistic one.

The FHB heads are not isolated structures. They have been reported to interact with surrounding soft tissues, where the medial head of the FHB contributed to the abductor hallucis (AbH; (Agawany *et al.*, 2010; Brenner, 1999; Ger, 1988), and the lateral head contributed to the adductor hallucis (AdH; (Cralley *et al.*, 1979; Ger, 1988; Owens *et al.*, 2001) tendons. These interactions with contiguous muscles for both FHB heads were described as difficult to differentiate from one another (Owens *et al.*, 2001). The lateral head of the FHB has been described as reaching distally with the AdH tendon to attach onto the proximal phalanx as a “conjoined” tendon (Nery *et al.*, 2017; Owens *et al.*, 2001). Additional robust interactions of the FHB have been reported with the plantar aponeurosis, acting on the windlass mechanism and contributing to the elevation of the medial longitudinal arch of the foot, (Chen *et al.*, 2014; Fukumoto *et al.*, 2020). The role of the FHB in the medial longitudinal arch suggests that the FHB tendons attach to the HS or surrounding tissues in a meaningful way, to act effectively onto the base of the proximal phalanx to act on the windlass mechanism (Hicks, 1954). The nature of this interaction has not been well reported, but it has been suggested that the FHB interacts with a fibrous tunnel before reaching the sesamoids (Kelikian *et al.*, 2011), which may be part of the plantar aponeurosis.

The FHB heads are involved in a number of pathologies, such as turf toe and other hyperextension injuries of the first MTPJ (Dockery, 1978; Pinter *et al.*, 2020), calcific tendinosis (Garner *et al.*, 2013), and have a direct

implication in conditions affecting the HS, such as HS fractures and consequently nonunion, by exerting distracting forces upon the fracture fragments (Bronner *et al.*, 2007; Cohen, 2009; Dedmond *et al.*, 2006; Pagenstert *et al.*, 2008). Depending on the fracture pattern to the HS, the attachment sites on the HS surfaces would help identify what muscles were most at risk of causing nonunion through their activation, since the bones are not purely encased in fibrous tissue but are rather attached to by numerous active and passive structures. Additionally, the type of footwear worn by an individual has been said to be a potential cause of pain from the FHB due to excessive overuse (Colò *et al.*, 2021).

Research on the attachments of the FHB has previously been carried out, measuring the longitudinal lengths of the “distal footprints” of the FHB on the proximal phalanx (Barták *et al.*, 2011; de Bengoa Vallejo *et al.*, 2012; DeMore III *et al.*, 2012). This was done to measure the average distal endpoints of the attachments of the FHB on the proximal phalanx, in order to identify optimal points or lines for proximal phalanx resection. These resections are carried out during surgeries such as Keller resections, implant arthroplasty, arthrodesis, or PPh base osteotomies in hallux valgus, to prevent functional loss at the first ray (de Bengoa Vallejo *et al.*, 2012). The focus of these studies, and of these surgeries, is on the attachments of the FHB tendons to the proximal phalanx, however no data is provided regarding the attachments of the FHB tendons to the HS or the nature of the footprints on the proximal phalanx. An accurate map of these footprints could help avoid unnecessary loss of function to the FHB during proximal phalanx

resections (de Bengoa Vallejo *et al.*, 2012; Hakim-Zargar *et al.*, 2010). There are also other well-known sequelae to damaging the FHB tendons, such as functional loss and cock-up toe deformity, especially during sesamoid excisions (Aper *et al.*, 1996; Dedmond *et al.*, 2006; Hakim-Zargar *et al.*, 2010; Owens *et al.*, 2001; Saxena *et al.*, 2003).

A common theme is seen, where the respective lateral and medial heads of the FHB lack clear, consistent, qualitative or quantitative data for the interactions they have with the HS and the proximal phalanx, as well as their contiguous tissues. The aim of this research is to map the footprints of the FHB to their distal bony attachments and identify their relationships to inform better surgical outcomes to the first MTPJ.

3.3.2 Material and Methods

Feet from embalmed (Genelyn Anatomical Series, Australia; see Appendix 1) Body Donors (n = 21; F = 12, M = 9; mean age = 82.1 years) were examined in accordance with *Part IV of the Human Tissue Act (1992)* and with local ethics approval (project ID: 12292). The flexor hallucis brevis muscles and tendons are implicated in deformities of the first ray and pathologies of the hallucal sesamoids, as such exclusion criteria included any signs of previous surgery, ulcers, hyperostosis or obvious, visual hallux valgus or hallux varus, as well as conditions that affect the morphology of the first ray such as hammer toe and or cock-up toe deformity. Specimens were screened via in-lab x-ray in order to exclude specimens with signs of first ray degeneration and abnormal sesamoid position (see Appendix 5.10).

The feet were CT scanned with a Siemens Biograph 128-slice ultraHD-PET CT scanner (Siemens, Germany; see Appendix 11) in order to segment bone surfaces for 3D modelling. Skin was removed from the medial and plantar aspects of the foot from the base of the first and second metatarsals to the distal phalanx of the first ray. A plantar approach uncovered the plantar aponeurosis, which was cleared and cut transversely just distal to the calcaneus and reflected distally. A medial approach was taken onto the medial surface of the AbH muscle. A fascicular dissection strategy (see Appendix 2) was employed to follow along the superficial surface of the structure. Fascicular dissection involved the direct observation of individual tissue fascicles under magnification. Decision-making regarding

tissue retention or removal was based on the course of specific fascicles. A surgical microscope (Wild Heerbrugg M651, Switzerland) was used to observe these tissues under 7-36x magnification, as required. Tissues were dissected until fascicles terminated, either in skeletal attachment, or by converging with other soft tissues. Once the medial surface of the AbH had been uncovered, at the level of the midfoot the dissection proceeded to the lateral surface of the AbH contiguous with the medial plantar intermuscular septum separating it from the medial head of the FHB, the lateral head of the FHB muscle was identified by the slight change of fascicle direction and the separation of the distal tendons, separated by the deep branch of the medial plantar artery at the level of the first metatarsal neck. Once confidently identified both FHB heads had their fibres followed distally, at the level of the medial and lateral sesamoids any fibres attaching to the sesamoid bones were followed to the bone and any other tissue relations were noted. At each level of dissection, attachments to bone were carefully clarified by removing any soft tissue, including periosteum, at the periphery of each attachment "footprint". If this peripheral tissue was associated with another structure of interest, the border was marked with ink. The target structure was cut to leave a minimal stump, facilitating direct observation of the complete circumference of the footprint at once. At each stage of dissection, the target tissue was described and photographed (EOS 5D mark III, Canon, Japan).

The FHB footprints on the medial and lateral sesamoids were outlined and modelled into a virtual 3D space using a digital microscribe (Microscribe G2X, ImmersionCorp, USA; see Appendix 3). The microscribe recorded the

3D coordinates of a single point into a virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA). A sequence of points located along a surface were converted into a digital line, and a series of digital lines used to render a model of a surface in the virtual environment. Utilising this process for each footprint not only rendered them in 3D, but allowed measurements of each to be taken, inclusive of their curvature. Footprints were modelled in triplicate to facilitate assessment of the accuracy and reproducibility of the process. Within the analysis, select images were reviewed by an expert team including anatomists and clinicians, but measurements carried out in triplicate were made by the author as a single intra-observer study. The area and perimeter of the footprint was measured in the virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA). To facilitate this process for the attachments, they were dissected off once their modelling sequence was complete. This facilitated clear observation, modelling and measurement of subsequent footprints.

The digital models of each footprint were then matched to their respective CT data. These data had been segmented and meshed to create models of the HS, proximal phalanx and first metatarsal. Overlying the bone models with the corresponding footprint models allowed visualisation of the complete array of footprints in three dimensions. The virtual environment software (Rhinoceros 4.0, Robert McNeel and Associates, USA) allowed for area measurements of the non-articular surface of each hallucal sesamoid and of each footprint model. Analysis of these data allowed for consideration

of each HS attachment as a percentage of the available hallucal sesamoid surface area.

To aid 3D visualisation of data, surface scans of relevant skeletal surfaces were created using a laser surface scanner (Artec3D, Luxembourg; see Appendices 5.6-5.9).

To determine the accuracy and reproducibility of the measurements and footprint modelling undertaken, all measurements and footprint models were done in triplicate. The data from each round of measurement/modelling were analysed for statistically significant differences at a standard confidence interval ($p = 0.05$).

3.3.3 Results

The medial FHB tendon was identified to have multiple interactions, most proximally the medial and plantar most fibres contributed to the deep surface of the AbH muscle and tendon, with muscle fibres proximally, then tendinous fibres distally (Figure 3.3.1). At the proximal pole of the MS, the FHB fibres ran through a plantar aponeurosis tunnel to reach the lateral MS surface, and occasionally through an AbH tunnel (Figure 3.3.2), with more proximal plantar-dorsal footprints on the proximal third on the MS (mean footprint $18.76 \pm 6.43 \text{ mm}^2$, 10% of MS non-articular surface). The medial FHB footprints were associated with the footprints of the plantar aponeurosis and the AbH in all cases ($n = 21$, 100%) (Figure 3.3.3), sometimes between separate plantar aponeurosis or AbH footprints (Figure 3.3.3B). Distal to the medial sesamoid, independent FHB slips were rarely identifiable ($n = 2$, 9%) (Figure 3.3.4), since the FHB distal tendons interdigitated with the AbH tendon and the plantar aponeurosis at the level of the proximal pole of the MS in all cases ($n = 21$, 100%).

The lateral FHB tendon was similar to the medial head, with many connections. In the midfoot, the lateral FHB muscle belly had interactions with the oblique head of the AdH muscle, and 10mm proximal to the lateral sesamoid, a more tendinous slip interdigitated with the AdH tendon in most cases (Figure 3.3.5). The tendon of the lateral FHB head approached the proximal pole, contiguous with many plantar aponeurosis fibres and attached onto the LS (mean attachment area = $20.73 \pm 6.96 \text{ mm}^2$)

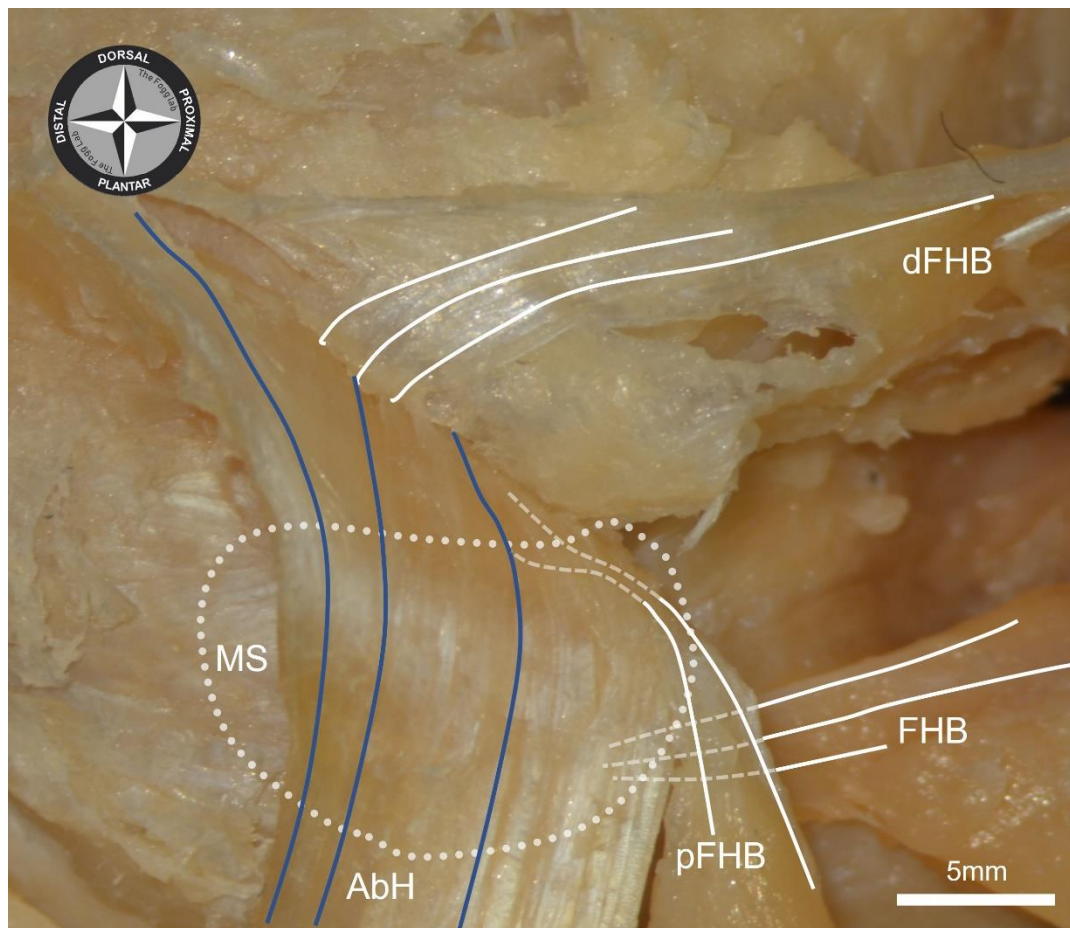


Figure 3.3.1. A medial view with the flexor hallucis brevis interdigitations (FHB, white lines) into the abductor hallucis (AbH, blue lines) reflected plantarly showing its deep surface highlighting the merging of thin FHB (dFHB) fibres, as well as a plantar bundle of FHB interdigitating with the AbH plantarly (pFHB). The only direct attachment to the medial sesamoid (MS, white dotted line) in this photograph was via a small bundle of fibres plantarly (FHB).

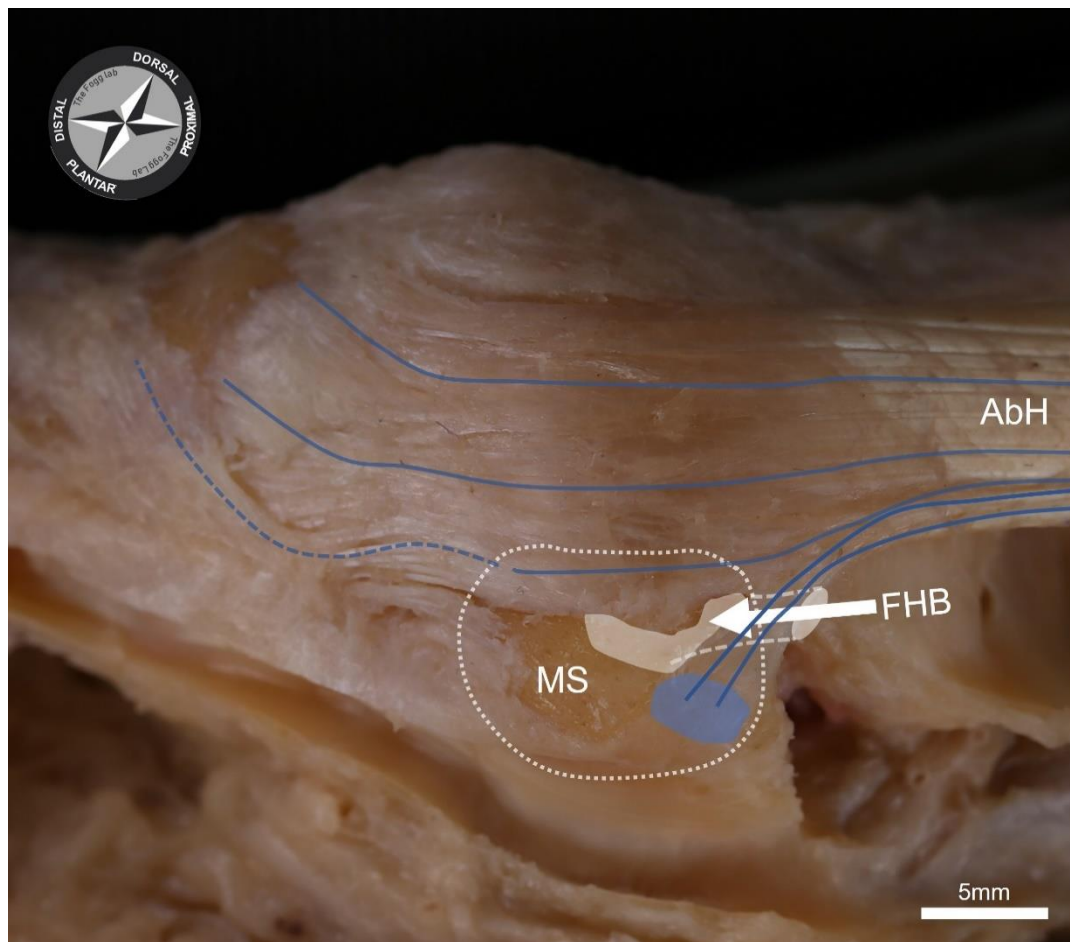


Figure 3.3.2. Medial view of the first metatarsophalangeal joint with the abductor hallucis (AbH, blue lines) attaching onto the medial sesamoid (MS, white dotted line) dorsally and plantarly with a separate slip (blue shadow). The separate slip creates a tunnel through which the flexor hallucis brevis (FHB) passed (white arrow) to attach onto the MS (white shadow).

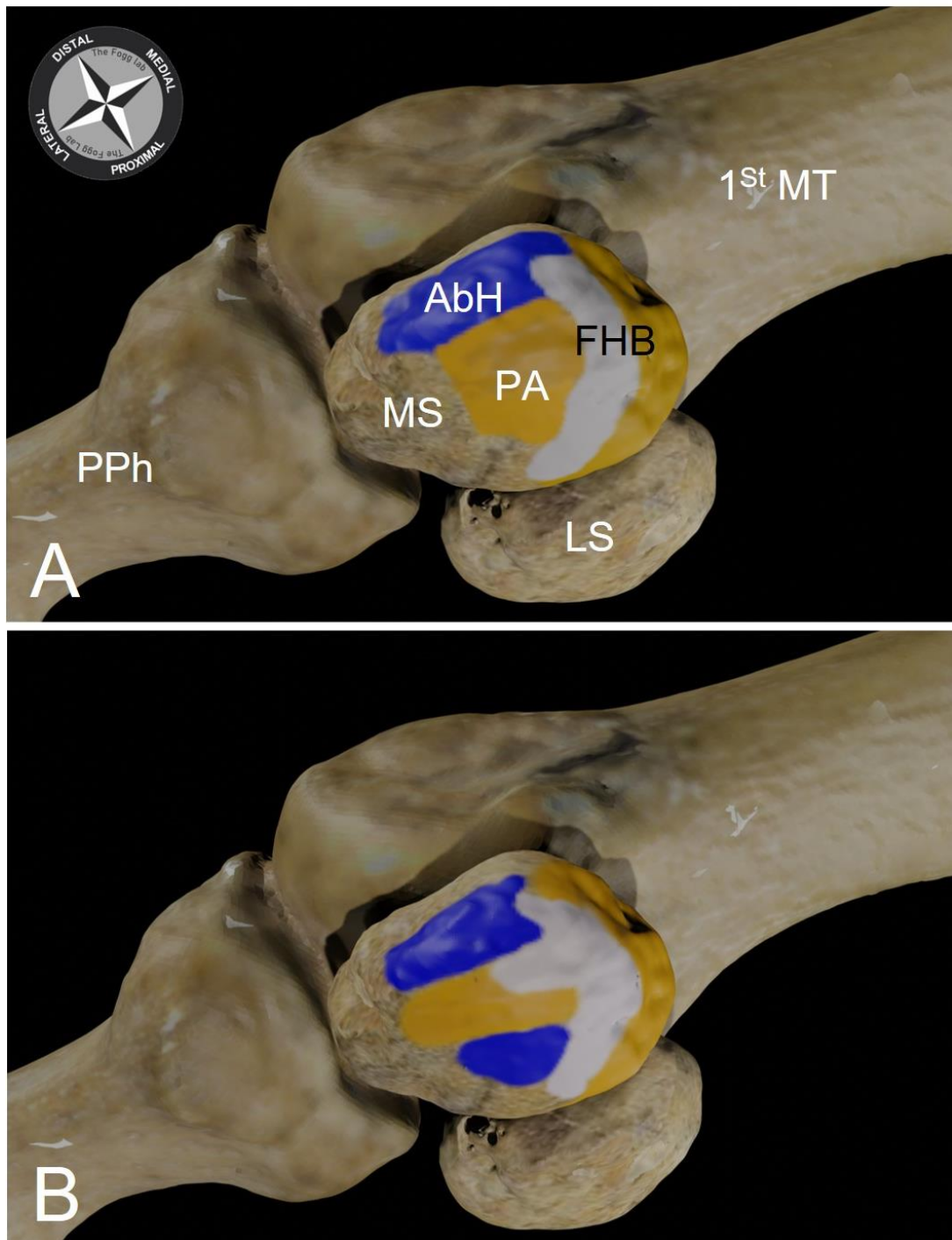


Figure 3.3.3. Plantar medial views of a 3D reconstruction of an osseous first metatarsophalangeal joint, highlighting attachment areas on the hallucal sesamoids. A and B are showing the two most common types of flexor hallucis brevis (FHB, white) attachment onto the proximal pole of the medial sesamoid (MS), showing the dorsal to plantar strip of attachment Area, the contiguous footprints were with the plantar aponeurosis (PA, orange) and the abductor hallucis (AbH, blue). In B, with a type B AbH attachment, the FHB extended further distally under the plantar AbH slip. LS: lateral sesamoid; PPh: proximal phalanx, 1st MT: first metatarsal.

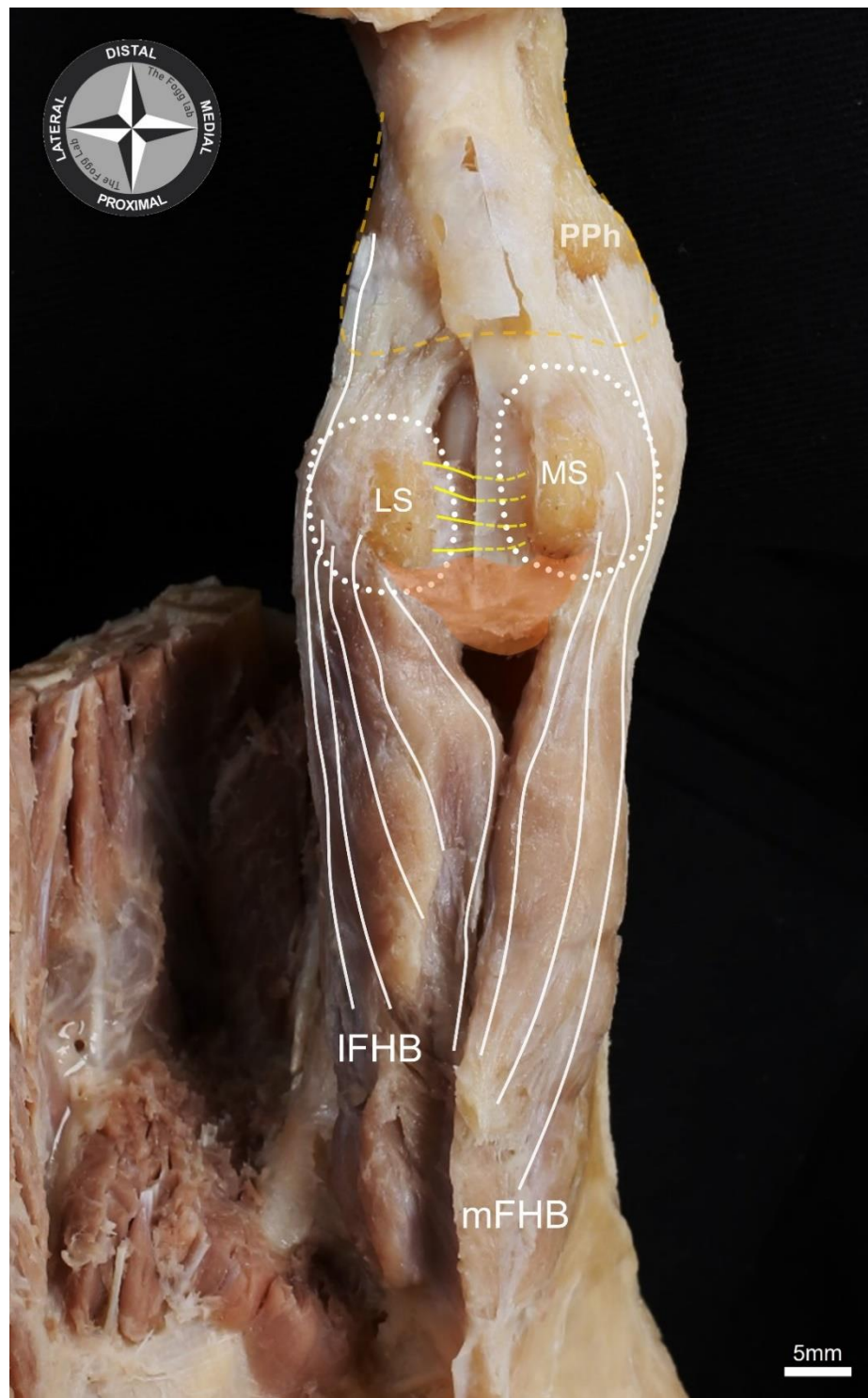


Figure 3.3.4. Plantar view of a dissected hallux, identifying prominent medial (mFHB) and lateral (IFHB) flexor hallucis brevis (FHB, white lines) attaching on the medial (MS) and lateral (LS) sesamoids (white dotted lines) and continuing distally on the margins of the joint to give fascicles to the proximal phalanx (PPh, orange dotted line). The FHB heads also contributed to the mass of plantar aponeurosis that was dissected out (orange shadow) proximal to the flexor hallucis longus tunnel roof and intersesamoid ligament (yellow lines)

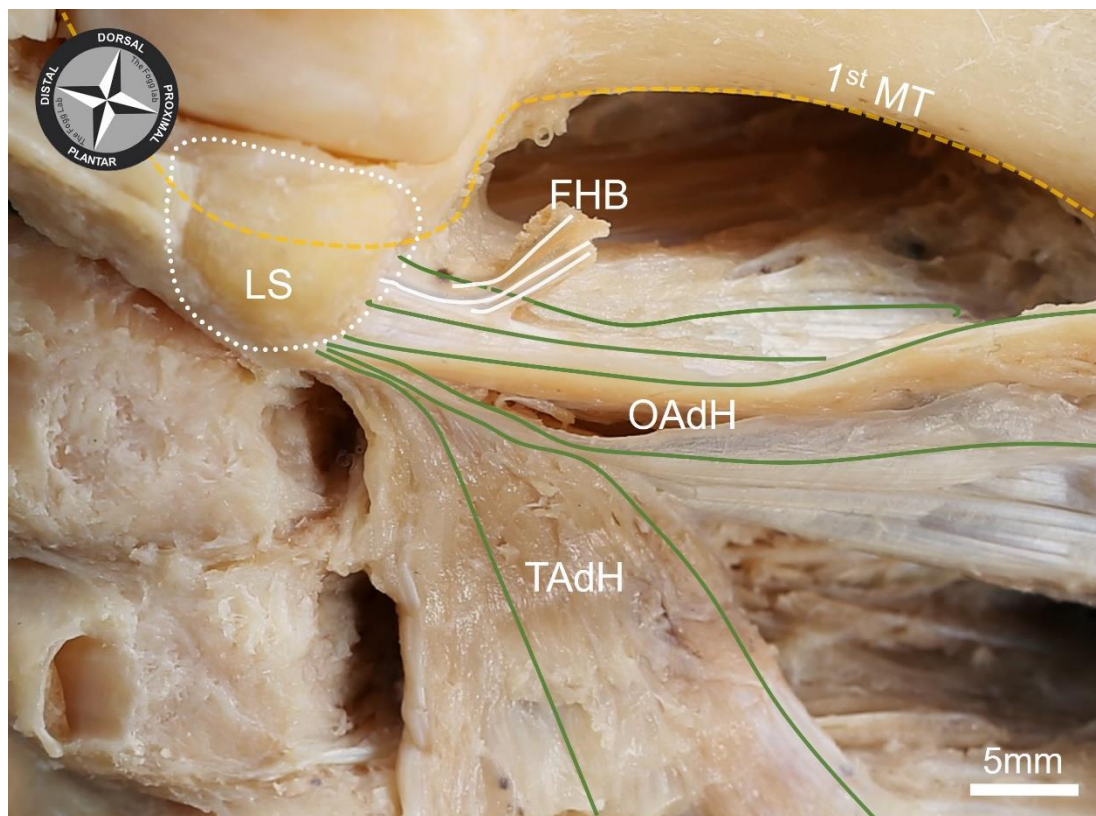


Figure 3.3.5. A plantar medial view of the ball of the foot dissected to highlight the adductor hallucis (AdH, green lines) attaching into the lateral sesamoid (LS, white dotted line) the junction of the transverse head (TAdH) and oblique head (OAdH) of the AdH muscle was seen. Immediately proximal to the LS, the fibres of the flexor hallucis brevis (FHB, white lines) tendon merged as a meaningful fibrous entity into the AdH.

covering approximately 16% of the non-articular surface of the LS. The footprint tended to be more longitudinal along the proximal pole, sometimes reaching the middle third of the lateral sesamoid (Figure 3.3.6). The FHB attachment was typically associated with the plantar aponeurosis proximally and the AdH distally; these associations were seen proximal to the lateral sesamoid in the form of interdigitations of small bundles of fascicles with these structures. Distal to the lateral sesamoid, very little in terms of FHB fascicles could be followed to the proximal phalanx; in two cases, distinct fascicles could be followed from the FHB to the proximal phalanx (Figures 3.3.4 and 3.3.7).

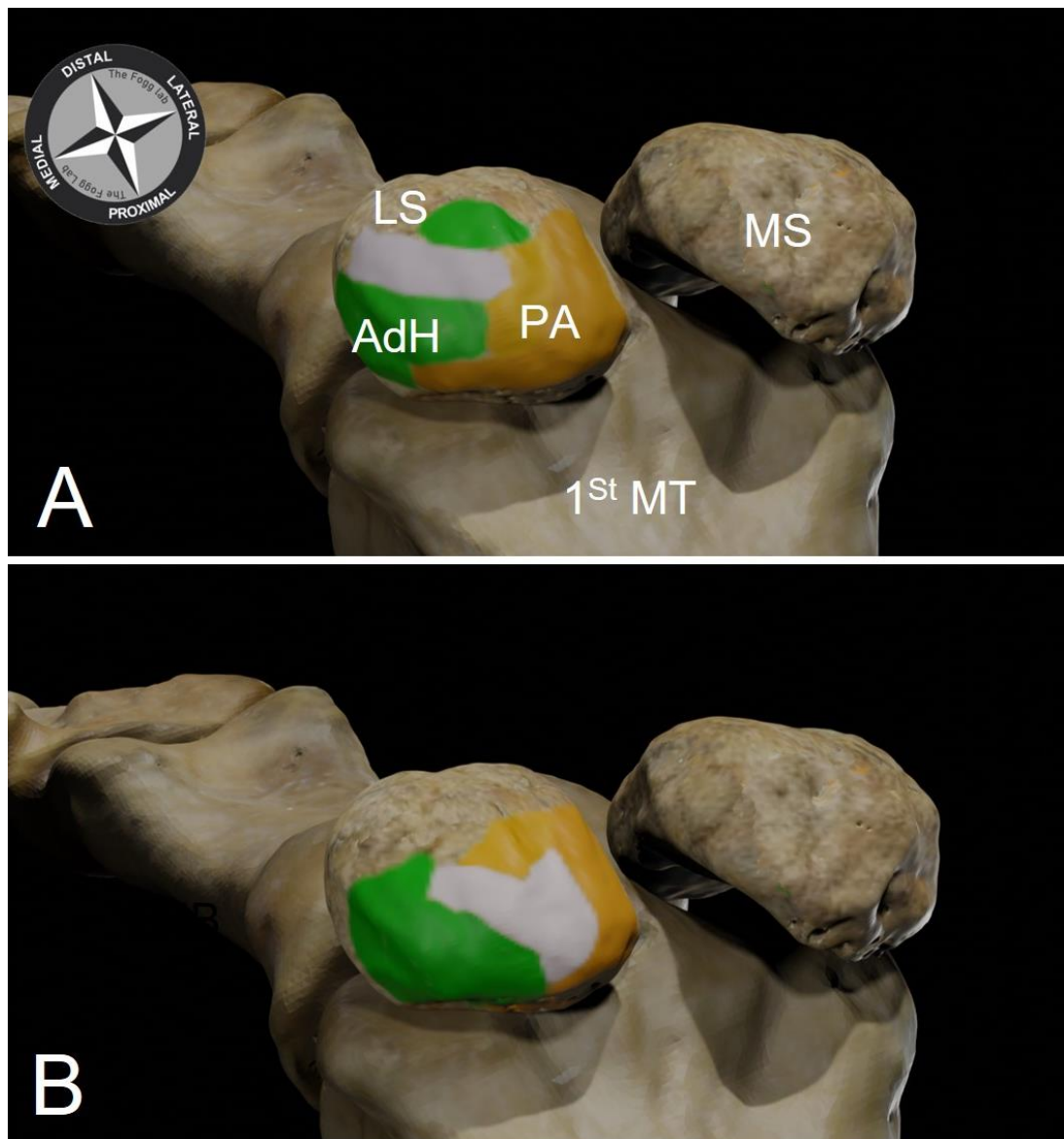


Figure 3.3.6. Proximo-plantar views of a 3D reconstruction of an osseous first metatarsophalangeal joint, highlighting attachment areas on the lateral sesamoid. A and B are showing the two most common types of flexor hallucis brevis (FHB, white) attachment onto the proximal pole of the lateral sesamoid (LS), showing a longitudinal attachment footprint. The contiguous footprints were with the plantar aponeurosis (PA, orange) and the adductor hallucis (AdH, green). MS: medial sesamoid; 1st MT: first metatarsal.

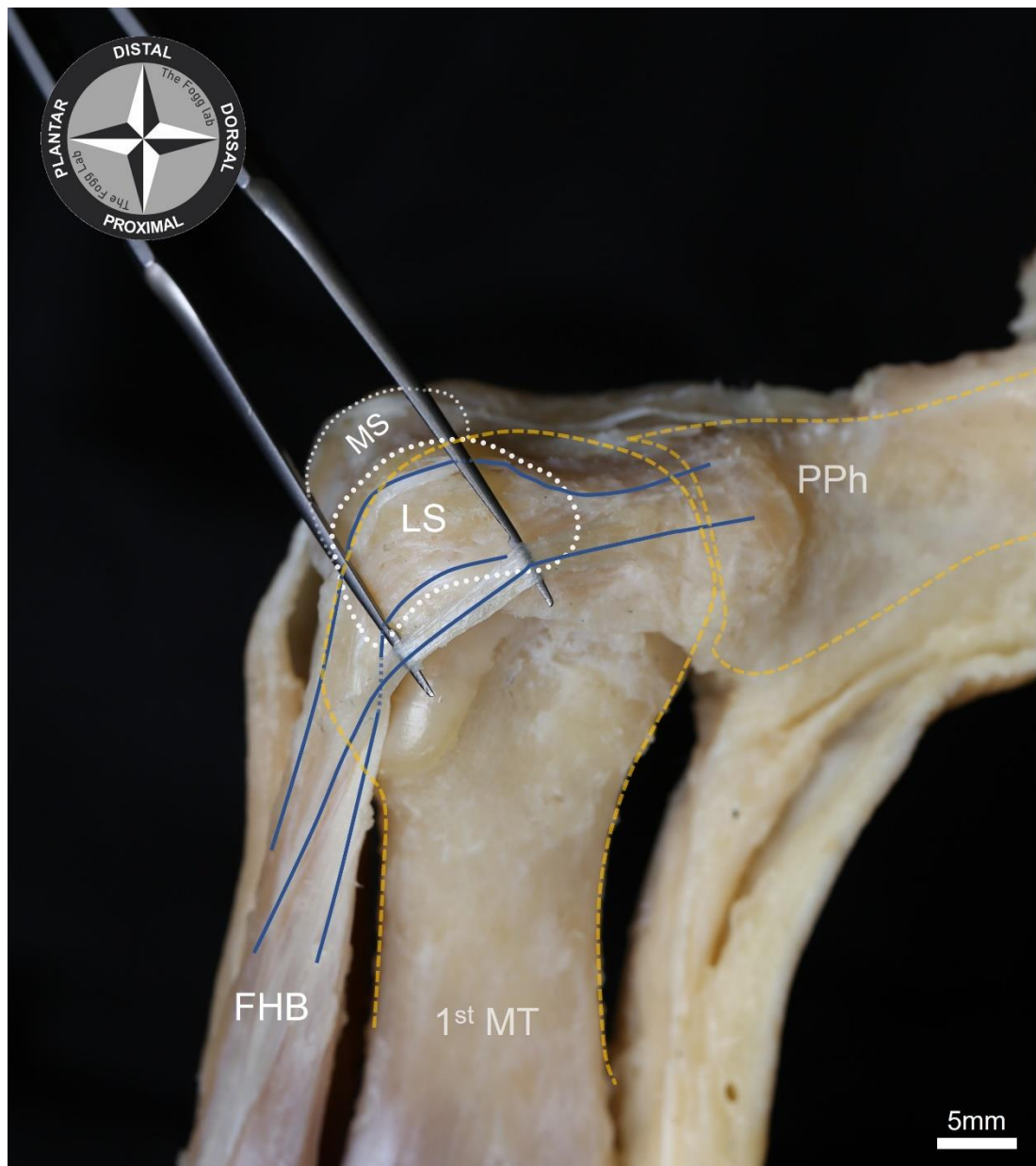


Figure 3.3.7. Lateral view of a dissected first metatarsophalangeal joint, with focus on the lateral head of the flexor hallucis brevis (FHB, white lines)) giving off superficial fascicles that reach distally to the proximal phalanx (PPh) over the lateral sesamoid (LS, white dotted line). Additional structures in view include the first metatarsal (1st MT) and the medial sesamoid (MS).

A few superficial fascicles were occasionally identified to contribute to the superficial medial collateral ligament (n=2, 9%; Figure 3.3.8A). There were a few instances (n=3, 14%) where a plantar set of fibres curved plantar then medial on the superficial surface of the distal third of the AbH muscle and tendon, these superficial fibres would then run dorsally to join extensor aponeurosis fibres (Figure 3.3.8B).

In summary, the FHB muscles had numerous interactions, with the medial FHB tendon contributing to the deep surface of the AbH muscle and tendon and to the plantar aponeurosis, as well as running through a tunnel of plantar aponeurosis and occasionally a tunnel created by the AbH tendon. The main attachment was to the proximal pole of the MS. The lateral FHB tendon contributed to the oblique head of the AdH muscle, and attached to the proximal pole with a more longitudinal footprint to that of the medial FHB tendon. This lateral attachment was contiguous with the plantar aponeurosis attachment in all cases. In very few specimens, distinct fibres could be followed to the PPh, as the FHB distal attachments commonly interdigitated with other structures before reaching distally, such as with the Abh, the Adh, the plantar aponeurosis and in rare cases on the medial side with the superficial medial collateral ligament or the extensor aponeurosis.

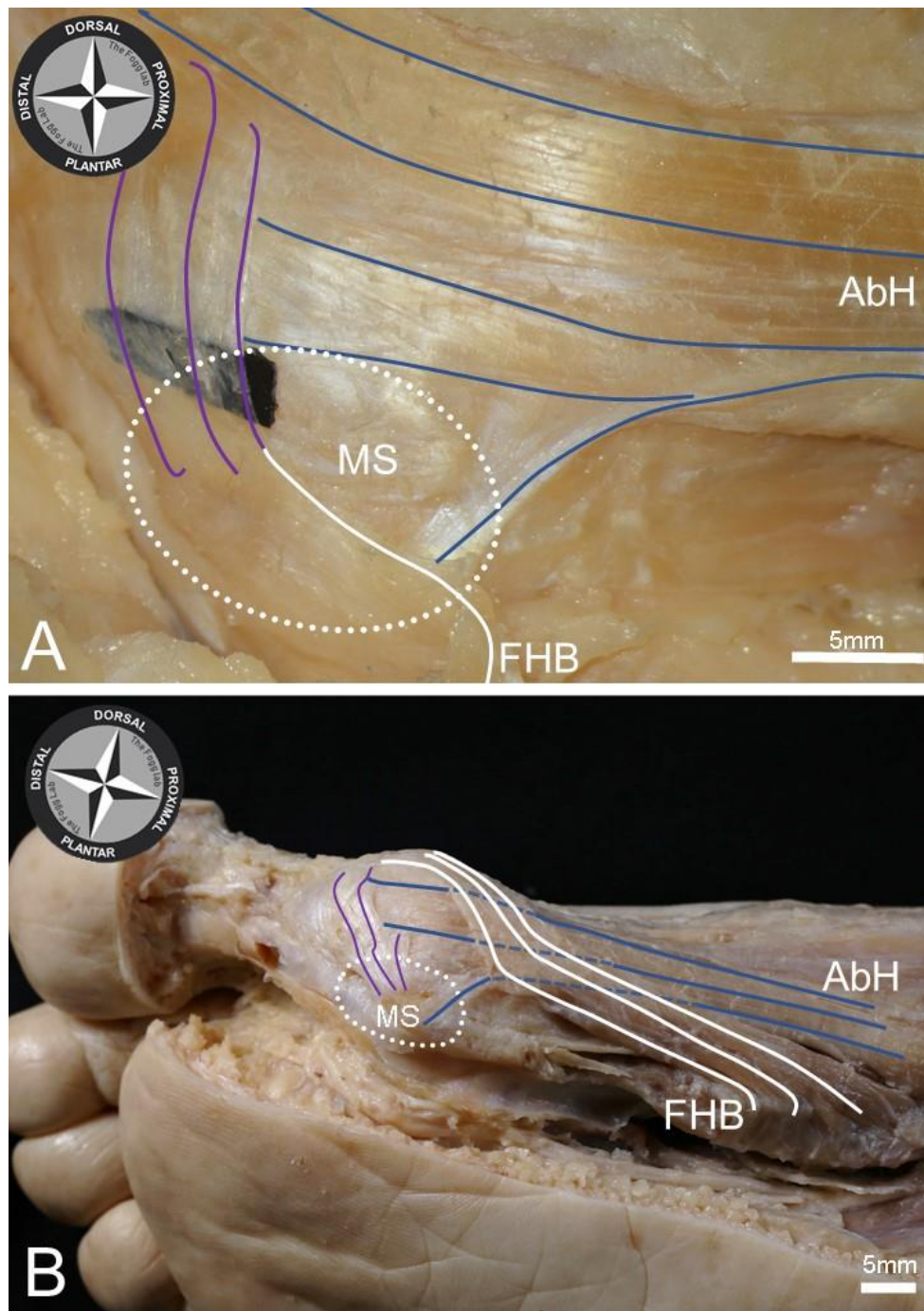


Figure 3.3.8. Unusual flexor hallucis brevis (FHB, white lines) interactions. A - Medial view of the first metatarsophalangeal joint at the level of the medial sesamoid (MS, white dotted line), highlighting the unusual fibres from a plantar-medial set of FHB contributing to the proximal most fibres of the type I superficial medial collateral ligament (purple lines) as it interdigitates with the fibres of the abductor hallucis (AbH, blue lines). B - Plantar medial view of the ball of the foot with the unusual FHB fibres curving plantar then medial on the superficial surface of the distal third of the AbH tendon, these superficial fibres then run dorsally to join extensor aponeurosis fibres along with the superficial medial collateral ligament (purple).

3.3.4 Discussion

The confidence in identifying the FHB heads and separating them from the adjoining tissues was built upon the fascicular dissection approach, in which individual fascicles were followed in order to make clear, reproducible decisions. Additionally, identifiable landmarks, such as the medial intermuscular septum, can be used to demarcate a plane between the AbH and the medial head of the FHB at the level of the midfoot. (Faymonville *et al.*, 2012; Kamel *et al.*, 1961). Defining the border between the two FHB heads was determined by the difference in fibre direction, which was more prominent at the tendinous parts, as well as the presence of an artery between both tendinous heads at the first metatarsal neck (Attinger *et al.*, 1997; Haines *et al.*, 1954; Pisani *et al.*, 2009). The lateral head of the FHB was differentiated from the oblique head of the AdH muscle by the interaction of the transverse head of the AdH distally and fibre direction. Once all muscles were confidently identified, the fascicular approach ensured that all further connections were clearly identified.

The consistent use of a dissection technique using clear landmarks and decision-making criteria may produce reproducible borders and patterns of interactions. Previous works regarding the attachments of the FHB did not describe their techniques accurately, and often sought the FHB fibres distal to the HS (Barták *et al.*, 2011; de Bengoa Vallejo *et al.*, 2012; DeMore III *et al.*, 2012). With the current study, it was observed that the FHB tendons rarely continued distal to the HS as individual fascicles, usually interdigitated within the substance of the contiguous organised fascicular tissues of the

AbH, AdH and the plantar aponeurosis. An investigation that started distal to the HS would make clear identification of the true FHB tendon fibres unlikely, and therefore observation of FHB footprints on the proximal phalanx impossible. The previous work on the FHB “footprints” does not represent a measure of FHB tendon attachment onto the proximal phalanx, but that of mixed fibrous tissues, avoiding these “footprints” on the proximal phalanx during resections is still important in avoiding negative outcomes post-operatively, but is not a FHB-preserving strategy alone.

Fractures at the HS are typically transverse and mid-waist on the sesamoid. Nonunion of these fractures are a complication of HS fracture (Anderson *et al.*, 2007; Pagenstert *et al.*, 2008; Waizy *et al.*, 2008) that is characterised by resorption at the fracture site, apparent widening of the fracture cleft, and sclerosis of the appositional bone surfaces (Taylor *et al.*, 2014). Nonunions are treated by bone grafting, screw fixation (Pagenstert *et al.*, 2008), or sesamoid excision (Anderson *et al.*, 2007; Aper *et al.*, 1996). Part of the recovery of an individual post fracture is a regimen of rest and immobilisation of the foot in question (Anderson *et al.*, 2007; Cohen, 2009). This is in the aim of preventing undue stress on the fragments, in order to keep good apposition and maintain reduction of the fracture surfaces. It is known that the FHB plays a role in non-union of HS fractures, but it is not known exactly where the FHB interacts with the HS; this study permits a clear visualisation of direct FHB tendon attachment into the HS and the interactions the FHB heads have with surrounding tissues. The footprints are a relatively small proportion of the attachments onto the HS (10% and 16%

for the medial and lateral sesamoids respectively), suggestive that the AbH and AdH tendons, as well as the fibrous tissues of the plantar aponeurosis, play more of a role in HS fracture nonunion than currently described. This theory can be expanded to other complications involving the FHB, such as bipartite sesamoid diastasis, cock-up toe, and hallux varus deformities (Dedmond *et al.*, 2006; Rodeo *et al.*, 1993; Saxena *et al.*, 2003), lowering the significance of the FHB in the development of these conditions. The small attachment surface of the FHB onto the HS is contrary to the belief of many that suggest the HS to be fully encased within the FHB tendons, i.e. having the totality of their non-articular surface being the footprint site for the FHB tendons (Anwar *et al.*, 2005; Athanasiou *et al.*, 1998; Dedmond *et al.*, 2006; Feldman *et al.*, 1970; Inge *et al.*, 1933; Jahss, 1981; Lucas *et al.*, 2014; Powers, 1934; Richardson, 1999; Scranton *et al.*, 1980; Van Hal *et al.*, 1982; York *et al.*, 2017).

The described FHB tendon interactions with the plantar aponeurosis and the intimate association of their respective footprints on both HS suggests that they are not functionally independent from one another. This confirms some previous findings regarding the role of the FHB in the medial longitudinal arch (Chen *et al.*, 2014; Fukumoto *et al.*, 2020), where the FHB was an active component of the arch, but conversely, damage to the investing parts of the plantar aponeurosis to the HS may affect FHB function.

This research was not without limitations the Donors studied came from a sample population with a high mean age (82.1 years), which may be

responsible in the differences in muscle morphology and occasional fascicle variation. The high age may lead to FHB fascicles being smaller, thinner and/or weaker, comparisons with a younger sample population would be welcomed. The slight difference in footprint shape between the medial more proximal dorsal plantar footprints and the lateral more longitudinal footprints has not been explained from our data. Biomechanical studies of the relative strengths of the medial and lateral FHB tendons independent of other fibrous tissues at the first MTPJ would clarify the functional capabilities of the FHB heads relative to each other and the AbH, AdH and plantar aponeurosis. The combined dissection and digital modelling approach facilitated the detailed assessment of the SMCL in three dimensions and allowed for a reconstructive approach to visualising dissection data. Despite these advantages, the dissection process remains destructive. Future studies could include sectional analysis (macro-sections, histology, diceCT, etc.) to observe tissue interrelations with less investigative disruptions. Comparison data from these approaches would provide a more comprehensive account of the detailed anatomy. Within this study, only intra-observer variation was assessed, future studies can include interobserver observation on key findings.

This research has outlined the relationships of the distal FHB and mapped its footprints on the HS. This will clarify the individual roles of the fibrous tissues at the HS and first proximal phalanx, helping clinicians make more informed decisions regarding FHB injury and HS fractures, as well as first proximal phalanx resections.

3.3.5 References

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Part Three, Chapter Four

3.4 Plantar Aponeurosis

3.4.1 Introduction

The plantar aponeurosis (PA) is a complex structure with many different relationships both superficially and deep on the plantar aspect of the foot. The suggested function of the PA is one of longitudinal arch stability, as well as helping during toe off {Hedrick, 1996 #457}. In the reviewed literature the PA was most commonly subdivided into lateral, central, and medial components (Chen *et al.*, 2014; Do Carmo *et al.*, 2008; Fukumoto *et al.*, 2020). The largest and most obvious component of the PA that may interact with the hallucal sesamoids (HS) was the central component (Chen *et al.*, 2014; Fukumoto *et al.*, 2020; Hicks, 1954), which will be the main component referred to in this study. The proximal attachment of the PA was well documented at the posterior aspect of the medial tuberosity of the calcaneus (Do Carmo *et al.*, 2008; Murphy *et al.*, 1998; Theodorou *et al.*, 2000), whereas distally, the attachments were not as clear. Plantarly in the forefoot, reports suggested that it split into five digital bundles, or longitudinal deep fibres, of the plantar aponeurosis to each of the lesser toes, including one for the hallux (Chen *et al.*, 2014; Do Carmo *et al.*, 2008; Hicks, 1954). This medial hallucal digital bundle was the main and most important bundle (Do Carmo *et al.*, 2008; Hicks, 1954), and was found to be thicker and wider than the other four bundles to the lesser toes (Chen *et al.*, 2014). Distally along the hallucal bundle, it was split again on either side of the long flexor tendon

into digital bands, otherwise known as sagittal septae, or fascial slips (Haines *et al.*, 1954; Hicks, 1954; Stainsby, 1997). These digital bands were reported to attach to the proximal-most point of the first proximal phalanx (PPh) or HS (Do Carmo *et al.*, 2008; Kelikian *et al.*, 2011; Samojla, 1994; Stainsby, 1997), onto the medial and lateral sides of the proximal most edge of the PPh or HS (Haines *et al.*, 1954), or, simply, directly into the articular capsule and the base of the PPh (Schneider, 2013). The most medial of the digital bands were also reported to attach distally to the medial sesamoid (MS) and continued onto the “*conjoined tendon*”, described as the tendons of the abductor hallucis (AdH) muscle and the medial head of the flexor hallucis brevis (FHB) muscle, which then distally reached the proximo-medial side of the PPh (Haines *et al.*, 1954). Similarly, the lateral digital band was reported to attach to the lateral sesamoid (LS), before it continued distally to the lateral plantar aspect of the base of the PPh (Haines *et al.*, 1954).

The PA was reported to be part of the makeup of the flexor hallucis longus (FHL) tunnel, where both the lateral and the medial digital bands to the hallux created a bridge of aponeurosis over the long flexor tendon, creating the plantar surface and entrance of FHL as it also formed the FHL tendon sheath (Haines *et al.*, 1954; Hedrick, 1996; Valvo *et al.*, 1987). These digital bands were also reported to interact with the fascia of the transverse head of the AdH muscle, the deep transverse metatarsal ligament (DTMTL), the collateral ligaments of the first metatarsophalangeal joint (MTPJ), and to be a major constituent of the plantar plates (Chen *et al.*, 2014; Kanatli *et al.*, 2006; Southerland *et al.*, 2012; Stainsby, 1997). Additionally, the digital

bands were reported to contribute meaningfully to both heads of the FHB muscle (Hedrick, 1996; Kelikian *et al.*, 2011). The nature of these connections is not well known.

The PA has an important role in maintaining longitudinal arch stability (Chen *et al.*, 2014; Fukumoto *et al.*, 2020; Hicks, 1954; Kogler *et al.*, 1996; Sarrafian, 1987), and is reported to be the main component of the windlass mechanism. During weightbearing at the metatarsal heads, the toes flex, as the weight spreads the longitudinal arch longitudinally, tightening the PA, which connects to the proximal phalanges, bringing the toes into flexion (Aquino *et al.*, 1999; Bojsen-Moller *et al.*, 1976; Hicks, 1954). While this occurs, the interphalangeal joints remained mobile, highlighting that the long flexor and extensors were not responsible (Hicks, 1954; Stainsby, 1997). Further to the longitudinal arch, the transverse arch across the metatarsal heads was reported to receive support from all five PA bundles in the form of medially and laterally sweeping fibres from the digital bands joining into the proximal edges of the deep transverse metatarsal ligaments (DTMTL; (Stainsby, 1997). This suggested that the plantar aponeurosis plays a role in the transverse arch of the foot and helps prevent undue forefoot splaying during weight-bearing (Stainsby, 1997).

The PA is involved in deformities of the foot such as hallux valgus, due to the reported attachments to the HS, maintaining an equal tension onto both HS, keeping them in line with the first MT head (Stainsby, 1997). During the progression of hallux valgus, the effect of the windlass mechanism

diminished, until, in severe cases, the windlass mechanism no longer had an effect, as the HS dissociated from the metatarsal head (Stainsby, 1997). Additionally, the medial longitudinal arch height diminished with hallux valgus progression, as the plantar aponeurosis slackened, no longer effectively keeping the arch up (Stainsby, 1997). The projections from the digital bands into the DTMTL played a role in maintaining the HS position, as the first metatarsal head deviates medially during hallux valgus, contributing to the subluxation of the HS complex from the first metatarsal head (Stainsby, 1997).

Due to the important biomechanical role of the plantar aponeurosis, it is preserved or repaired during surgery, such as in lateral release. The contributions of the digital bands to the DTMTL should be maintained, by avoiding the sectioning of the DTMTL between the first and second rays (Stainsby, 1997). In cases of recalcitrant HS fractures or degenerated HS, sesamoid excision is carried out (Stainsby, 1997; Taylor *et al.*, 2014). There is an understanding that during these procedures, that damage to the plantar plates interferes with both the action of the windlass mechanism, as well as other active and passive functions of the first MTPJ. This may, in turn, exacerbate conditions such as hallux valgus, hallux varus, or clawing deformities, and cause splaying at the forefoot (Stainsby, 1997; Taylor *et al.*, 2014).

Despite the discussed importance and mechanics of the plantar aponeurosis (Kelikian *et al.*, 2011; Kogler *et al.*, 1996), the exact distal attachments of the plantar aponeurosis within the hallux are not well understood and need clarification. The aim of this research was to trace the course of the plantar aponeurosis into the hallux and map its attachments distally.

3.4.2 Material and Methods

Feet from embalmed (Genelyn Anatomical Series, Australia; see Appendix 5.1) Body Donors (n = 21; F = 12, M = 9; mean age = 82.1 years) were examined in accordance with *Part IV of the Human Tissue Act (1992)* and with local ethics approval (project ID: 12292). The plantar aponeurosis is implicated in a number of conditions including plantar fasciitis and deformities at the forefoot, as such exclusion criteria included any signs of previous surgery, or obvious, visual hallux valgus or overt morphological variants of the plantar foot, or signs of scarring or osteophytic encroachment into the PA. Specimens were screened via in-lab x-ray (see Appendix 5.10).

The feet were CT scanned with a Siemens Biograph 128-slice ultraHD-PET CT scanner (Siemens, Germany; see Appendix 5.11) in order to segment bone surfaces for 3D modelling. Skin was removed from the medial and plantar aspects of the foot from the base of the first and second metatarsals to the distal phalanx of the first ray. Rays three through five were removed at the level of the midfoot (Figure 3.4.1). A plantar approach uncovered the thick central component of the PA, the plantar surface of which was cleared and followed distally into the hallux, discarding any structures superficial/plantar to the main PA bundles and slips that did not reach the first MTPJ. A fascicular dissection strategy (see Appendix 5.2) was employed to follow along the superficial surface of each structure. Fascicular dissection involved the direct observation of individual tissue fascicles under magnification. Decision-making regarding tissue retention or removal was

based on the course of specific fascicles. A surgical microscope (Wild Heerbrugg M651, Switzerland) was used to observe these tissues under 7-36x magnification, as required. Tissues were dissected until fascicles

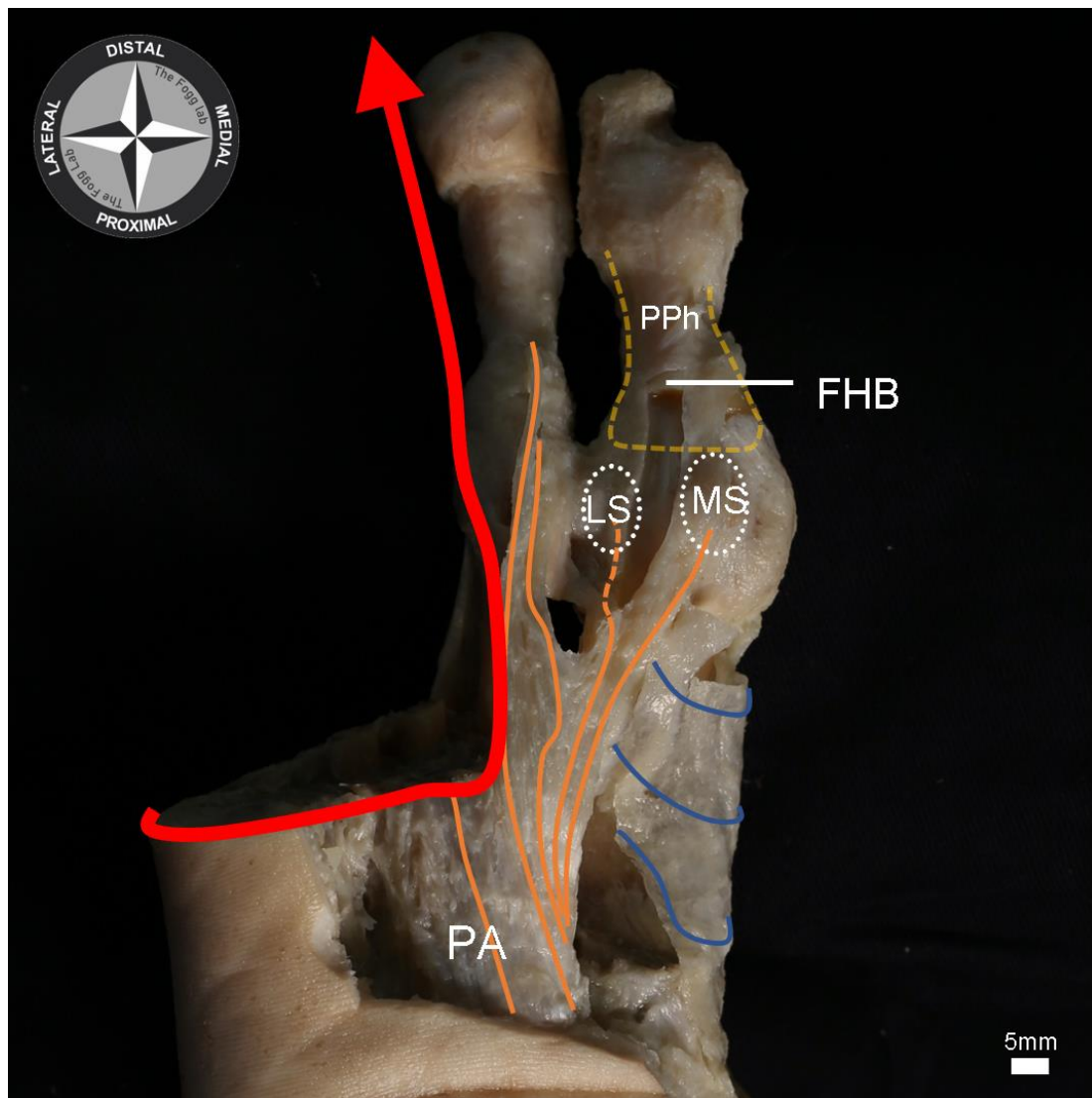


Figure 3.4.1. Plantar view of a dissected foot, highlighting sectioning line to remove rays three through five (red arrow), which cuts through the plantar aponeurosis (PA, orange lines) leaving the first and second digital bundles intact, with the first bundle reaching the hallux and the medial (MS) and lateral (LS) hallucal sesamoids, as well as the flexor hallucis longus (FHL) tunnel and the proximal phalanx (PPh, yellow dashed line).

terminated, either in skeletal attachment, or by converging with other soft tissues.

Once the medial surface of the plantar surface of the PA had been uncovered, at the level of the mid-metatarsal, the first bundle was sectioned transversely to follow its dorsal aspect distally, whilst noting and removing any deep muscular tissues. At the level of the MS and LS, any fibres attaching to the sesamoid bones were followed to the bone and any other tissue relations were noted. At each level of dissection, attachments to bone were carefully clarified by removing any soft tissue, including periosteum, at the periphery of each attachment “footprint”. If this peripheral tissue was associated with another structure of interest, the border was marked with ink. The target structure was cut to leave a minimal stump, facilitating direct observation of the complete circumference of the footprint at once. At each stage of dissection, the target tissue was described and photographed (EOS 5D mark III, Canon, Japan).

The PA footprints on the MS and LS were outlined and modelled into a virtual 3D space using a digital microscribe (Microscribe G2X, ImmersionCorp, USA; see Appendix 5.3). The microscribe recorded the 3D coordinates of a single point into a virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA). A sequence of points located along a surface were converted into a digital line, and a series of digital lines used to render a model of a surface in the virtual environment. Utilising this process

for each footprint not only rendered them in 3D, but allowed measurements of each to be taken, inclusive of their curvature. Footprints were modelled in triplicate to facilitate assessment of the accuracy and reproducibility of the process. Images were reviewed with an expert team including anatomists and clinicians, but measurements done in triplicate were done by the author as a single intra-observer study. The area and perimeter of the footprint was measured in the virtual environment (Rhinoceros 4.0, Robert McNeel and Associates, USA). To facilitate this process for the attachments, they were dissected off once their modelling sequence was complete. This facilitated clear observation, modelling and measurement of subsequent footprints.

The digital models of each footprint were then matched to their respective CT data. These data had been segmented and meshed to create models of the HS, proximal phalanx and first metatarsal. Overlying the bone models with the corresponding footprint models allowed visualisation of the complete array of footprints in three dimensions. The virtual environment software (Rhinoceros 4.0, Robert McNeel and Associates, USA) allowed for area measurements of the non-articular surface of each hallucal sesamoid and of each footprint model. Analysis of these data allowed for consideration of each HS attachment as a percentage of the available hallucal sesamoid surface area.

To aid 3D visualisation of data, surface scans of relevant skeletal surfaces were created using a laser surface scanner (Artec3D, Luxembourg; see Appendices 5.6-5.9).

To determine the accuracy and reproducibility of the measurements and footprint modelling undertaken, all measurements and footprint models were done in triplicate. The data from each round of measurement/modelling were analysed for statistically significant differences at a standard confidence interval ($p = 0.05$).

3.4.3 Results

The distal PA was a complex set of fibres, with some organised and some disorganised fibres, with clear and defined directional fibres and ambiguously directed amorphous looking tissue respectively. Attaching to numerous hard and soft tissue structures at the hallux. The first and second digital bundles reached the first and second rays respectively (Figures 3.4.1 and 3.4.2), but they were not limited to their respective rays, finding connections crossing over from one bundle to the other (Figure 3.4.2 and 3.4.3). The connections identified for the distal fibres of the first digital bundle included the abductor hallucis (AbH) medial muscular fascia attaching along the medial border of the bundle (Figures 3.4.1 and 3.4.2), the second ray PPh and second digital bundle (Figure 3.4.2), the FHL tunnel (Figures 3.4.1 and 3.4.2), the DTMTL (Figure 3.4.2), as well as the proximal aspect of the first MTPJ capsule, the intersesamoid ligament and the flexor hallucis brevis (FHB) tendon (Figure 3.4.3). These connections were often hard to follow as the tissues got more disorganised, as they separated from the longitudinal fibres of the main PA. This was especially true just proximal to the HS with the interactions of the PA with the FHB and first MTPJ capsule.

At the level of the FHL tunnel, two distinct bundles split on either side of the FHL tendon towards their respective HS. This split formed around the FHL and contributed along the remaining length of the tunnel (Figures 3.4.4 and 3.4.5). The fibres of the PA could be traced into the smooth fibro-cartilaginous dorsal roof of the FHL tunnel. These fibres were distinct from

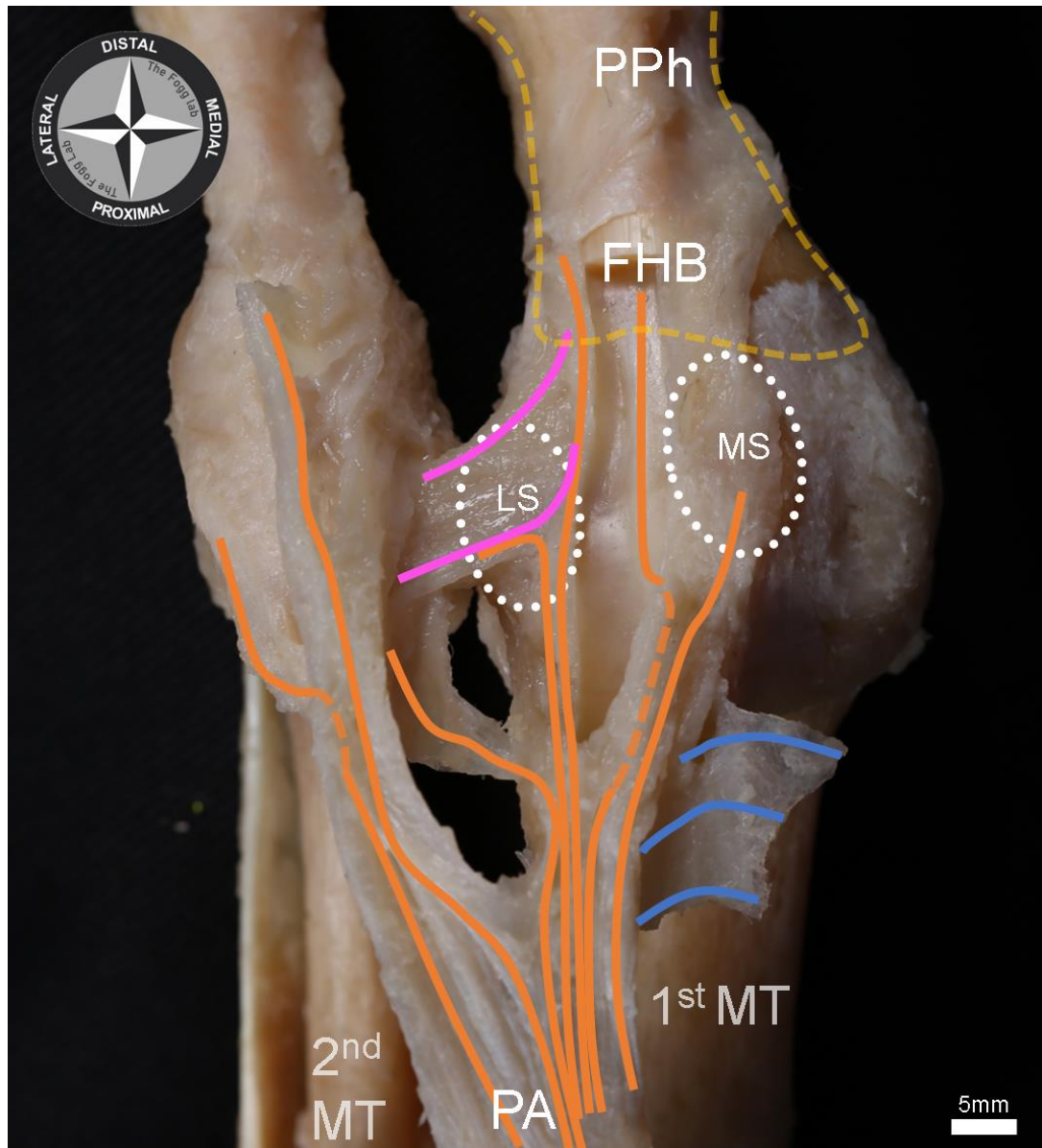


Figure 3.4.2. Plantar view of the first (1st MT) and second (2nd MT) metatarsals and their metatarsophalangeal joints with the plantar aponeurosis (PA, orange lines) dissected out, highlighting the connections to the abductor hallucis medial muscular fascia (blue lines) the second plantar plate, the deep transverse metatarsal ligament (pink lines), the medial (MS) and lateral (LS) sesamoids (white dotted lines) as well as the flexor hallucis longus (FHL) and its tunnel, towards the proximal phalanx (PPh, yellow dashed lines).

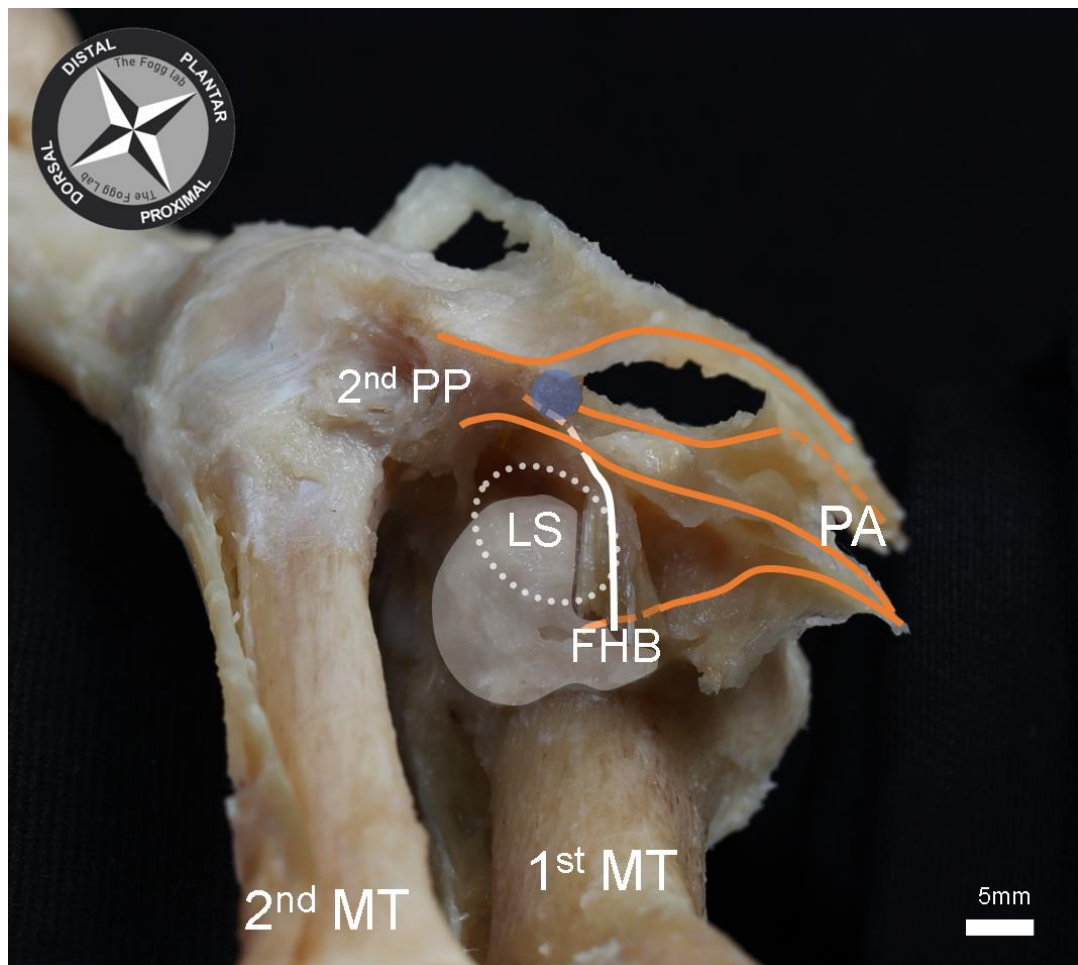


Figure 3.4.3. A proximal-plantar oblique view of the first (1st MT) and second (2nd MT) metatarsals and their metatarsophalangeal joints with the plantar aponeurosis (PA, orange lines) dissected out, highlighting the more dorsal interactions proximal to the lateral sesamoid (LS, white dotted line), such as the joint capsule (white shadow), the second plantar plate (2nd PP) as well as the first lumbrical (blue shadow), as well as small attachment from the flexor hallucis brevis (FHB, white line).

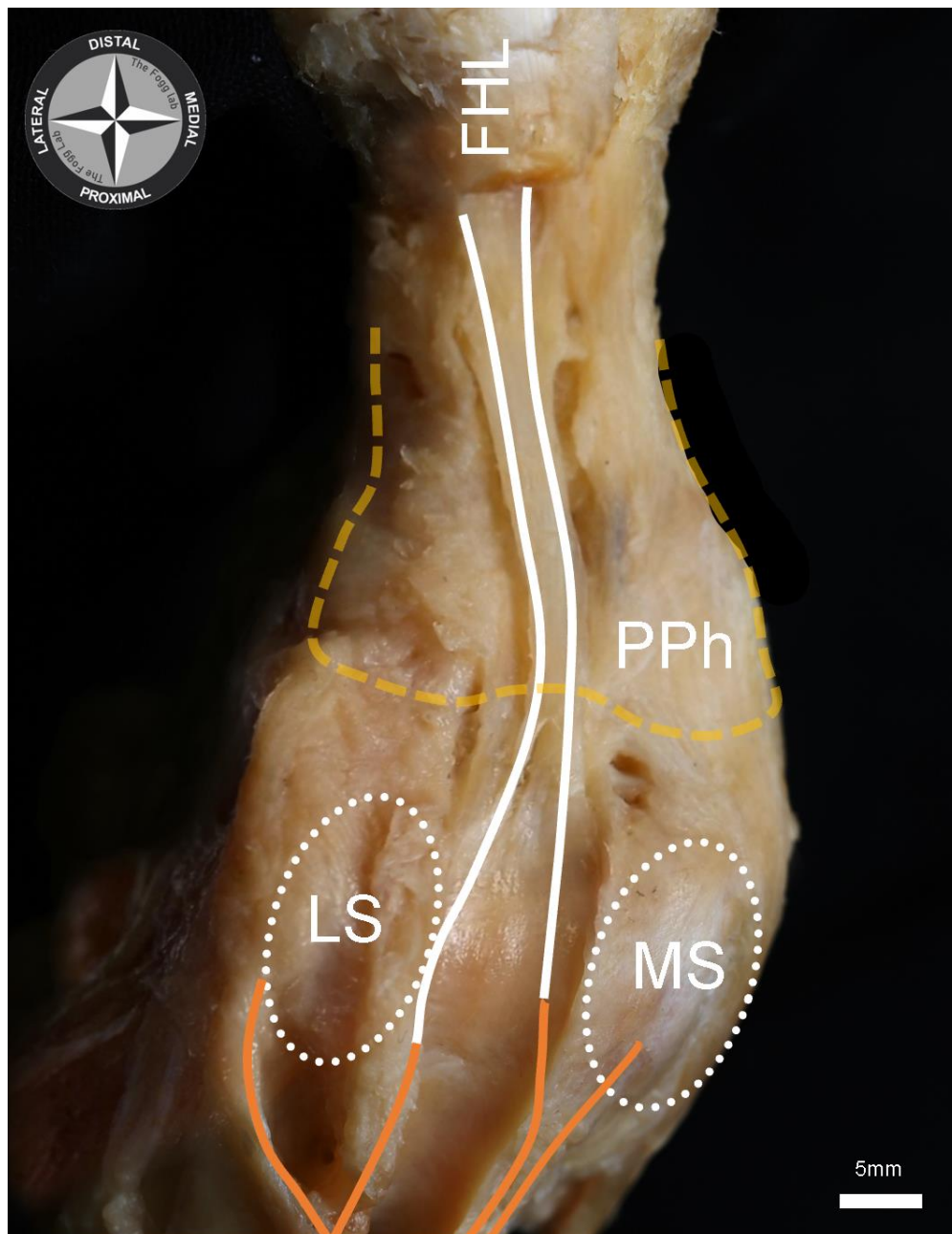


Figure 3.4.4. Plantar view of a first metatarsophalangeal joint and proximal phalanx (PPh, yellow dashed line) highlighting the course of the digital bands (orange lines) to the medial (MS) and lateral (LS) sesamoids as well as forming the dorsal roof of the flexor hallucis longus (FHL) tunnel (white lines) which has been lifted from the underlying tissues.

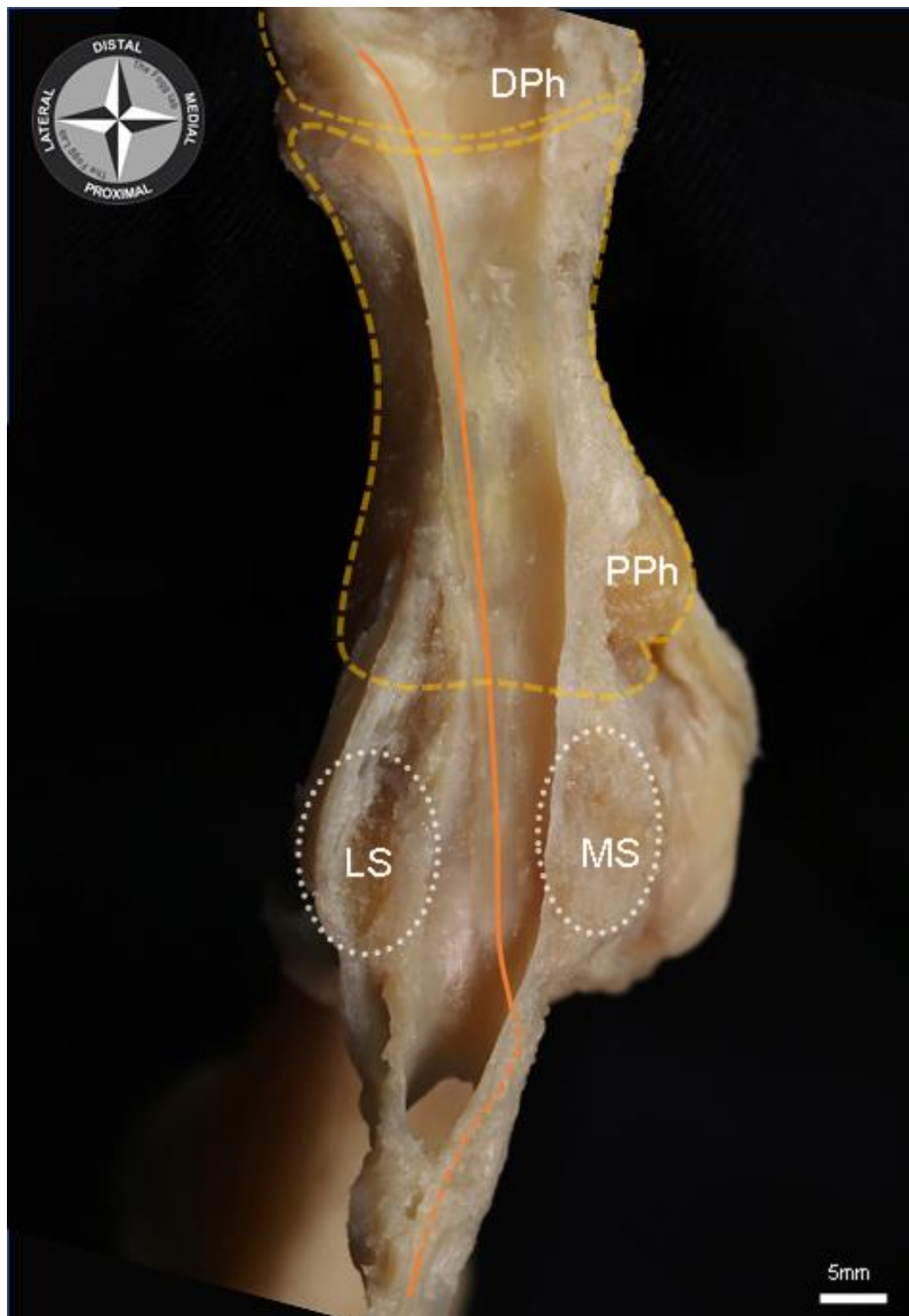


Figure 3.4.5. Plantar view of a first metatarsophalangeal joint and proximal phalanx (PPh, yellow dashed line) highlighting the course of the medial digital band (orange line) past the medial (MS) and lateral (LS) sesamoids, providing a single fascicle twisting around the flexor hallucis longus tunnel to attach onto the lateral aspect of the distal phalanx (DPH, yellow dashed line).

the sesamophalangeal ligaments dorsal to them and could be lifted quite easily (Figure 3.4.4). The course of the FHL tunnel roof fascicles could be made from the transverse orientation of the first digital bundle, twisting into a sagittal position around the FHL tendon, into a transverse orientation within the dorsal roof of the FHL tunnel. Here, the fascicles run distally until reaching the base of the distal phalanx (Figures 3.4.4 and 3.4.5). In one specimen, the fascicle from the medial digital band attached into the lateral aspect of the base of the distal phalanx (Figure 3.4.5). Other longitudinal fascicles within this smooth FHL roof were found to interdigitate into plantar parts of the inter-metatarsal ligament at a level between the HS.

At the level of the HS, the PA attached onto much of the proximal poles of both sesamoids, with extensive footprints contiguous with the intersesamoid ligament, the FHB, as well as the AdH and AbH footprints (Figure 3.4.6). The medial digital band attached onto the MS with two separate footprints (mean area = $50.39 \pm 14.91 \text{ mm}^2$, 26% of the total MS non articular surface). Whereas the lateral digital band attached onto the LS, with a single footprint (mean area = $27.53 \pm 6.09 \text{ mm}^2$, 19% of the total LS non articular surface; Figure 3.4.7).

The summary of the results is as follows: The PA separated into digital bundles as it reached distally, with one for the hallux and one for the second ray, where they both had crossing fibres from one bundle to the other. The first digital bundle interacted with many structures including the AbH muscle,

the first and second ray PPh and second digital bundle, the FHL tunnel, the DTMTL, the first MTPJ, the intersesamoid ligament and the FHB tendons. The PA created the opening of the FHL tunnel by splitting on either side of the FHL tendon, helping form the tunnel itself with traceable fibres within the dorsal roof of the FHL tunnel attaching distally into the intersesamoid ligament as well as the plantar aspect of the first PPh. A majority of the proximal poles of the HS were the bony attachment sites of the PA with two footprints on the MS and a single footprint on the LS

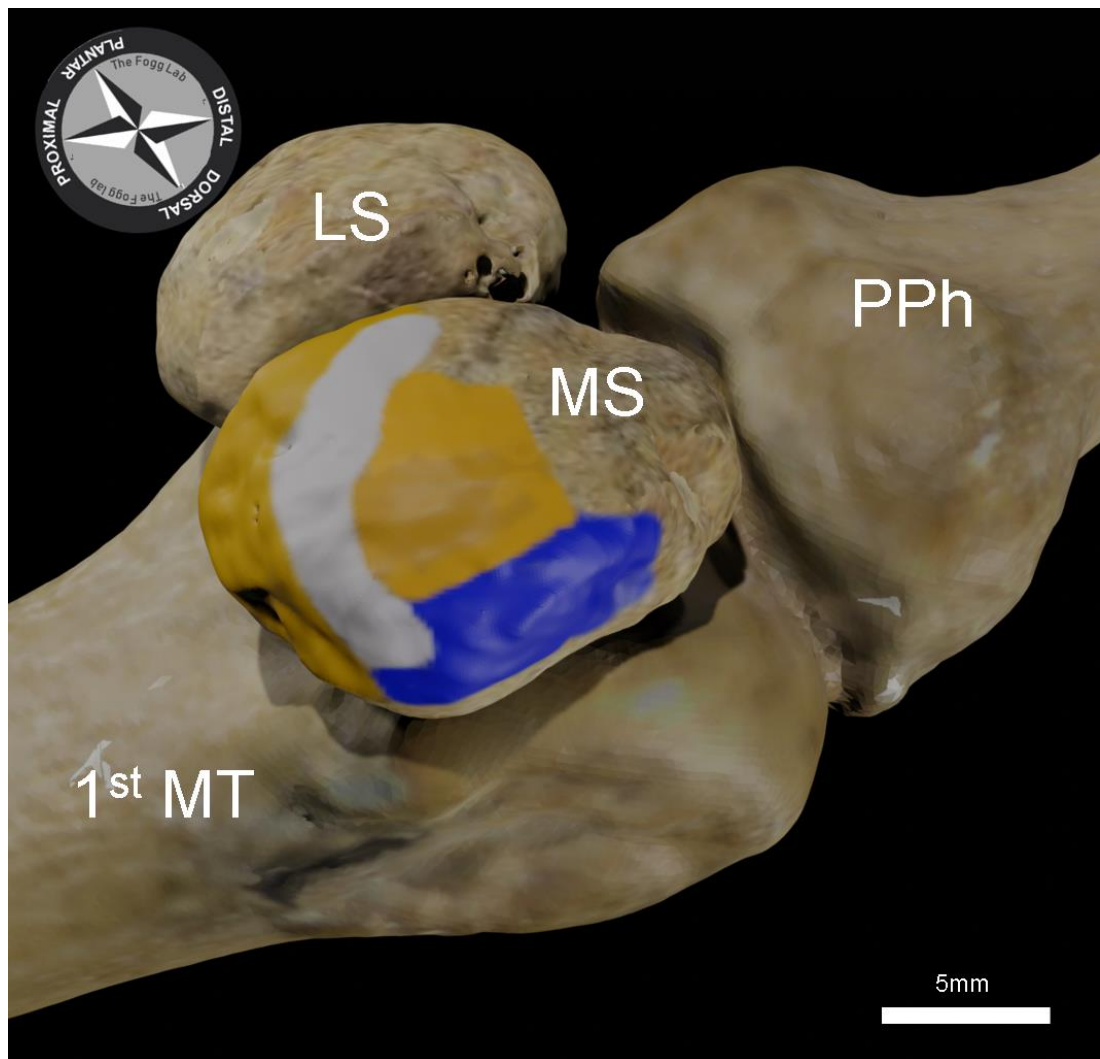


Figure 3.4.6. Plantar-medial view of a 3D model of the osseous first metatarsophalangeal joint showing the medial (MS) and lateral (LS) sesamoids, the first metatarsal (1st MT), and proximal phalanx (PPh). The MS received amalgamated footprints from the plantar aponeurosis (PA, orange) in two separate footprints, lying to either side of the flexor hallucis brevis footprint (FHB, white). Medial and dorsal to this, the abductor hallucis footprint (blue) was contiguous with PA and FHB attachments.

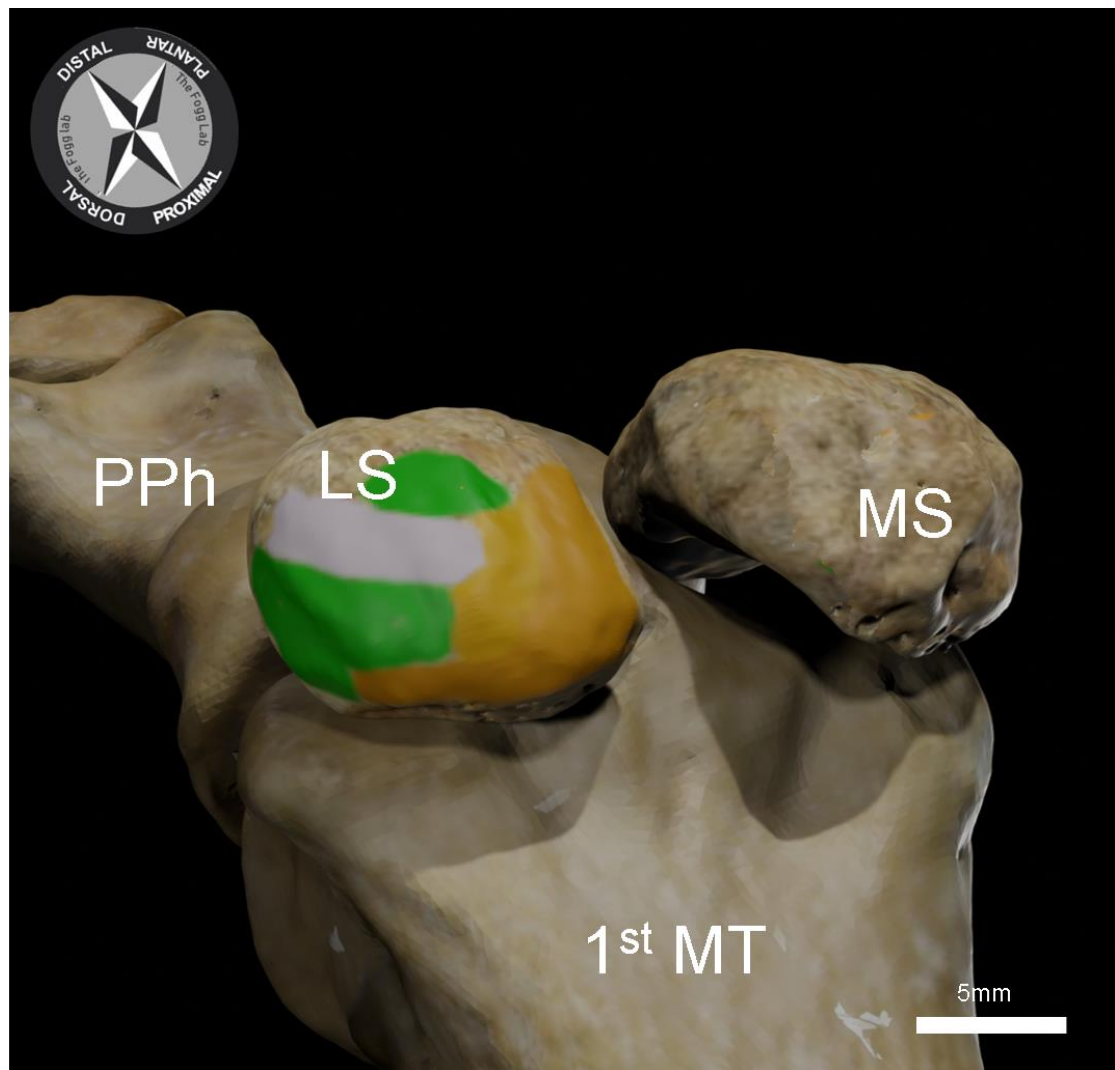


Figure 3.4.7. Plantar-lateral view of a 3D model of the osseous first metatarsophalangeal joint showing the medial (MS) and lateral (LS) sesamoids, the first metatarsal (1st MT) and proximal phalanx (PPh). The LS received amalgamated footprints from the plantar aponeurosis (orange), with a large proximal footprint contiguous with the flexor hallucis brevis footprint (white), and the adductor hallucis footprint (green), which was divided to either side of the flexor hallucis brevis attachment.

3.4.4 Discussion

The current data support the previous description of PA attachments into the first MTPJ articular capsule (Schneider, 2013)(Figure 3.4.3), the FHL tunnel (Haines *et al.*, 1954; Hedrick, 1996; Valvo *et al.*, 1987); Figures 3.4.1, 3.4.2, 3.4.4 and 3.4.5), the DTMTL (Figure 3.4.2;(Stainsby, 1997), the FHB tendon (Hedrick, 1996; Kelikian *et al.*, 2011);Figure 3.4.3) and the PPh (Schneider, 2013);Figure 3.4.5). The PA footprints were closely associated with those of the AdH and AbH tendons, confirming previously reported interactions (Haines *et al.*, 1954). Importantly, the reported interactions with the HS (Do Carmo *et al.*, 2008; Fukumoto *et al.*, 2020; Kelikian *et al.*, 2011; Samojla, 1994; Stainsby, 1997) were observed for both digital bands to their respective HS (Figures 3.4.6 and 3.4.7).

Discrepancies in reported distal attachment points for the plantar aponeurosis may be the result of the very complex nature of these interactions (Figure 3.4.2). The interactions were not always clear, as the PA was often composed of disorganised, irregular tissue that was diffusely arranged. The diffuse nature of the distal PA meant that it interacted with most structures at the hallux. The current study employed a very specific directional approach, combined with a fascicular dissection strategy, to carefully trace every fascicle of the PA associated with the first and second rays. But this did not always lead to clear interactions. Without this purposeful procedure it is extremely likely that many of these connections would be easily missed.

The reported interaction of the PA with the DTMTL was observed; however, additional connections were seen between the first digital bundle and the second plantar plate, in the form of organised tissue slips. In weight bearing, the plantar aponeurosis is said to tighten (Stainsby, 1997), such that the taut PA would pull on these distal interactions, helping stabilise many tissues at the hallux, as well as tightening the connection between the first ray and the second ray (Figures 3.4.2 and 3.4.3). This may help prevent undue splaying at the forefoot and contribute to the transverse arch of the foot. Disruption of these connections, such as in surgical release, may therefore contribute to decreased stability in this region, especially under dynamic conditions.

Previous research has shown that there is little impact when sectioning the medial aspect of the PA (Chen *et al.*, 2014), which seems counterintuitive, considering the importance of the first digital bundle to the hallux (Do Carmo *et al.*, 2008; Hicks, 1954), and the windlass mechanism no longer has any effect in severe hallux valgus (Stainsby, 1997). These sectioning studies may not have specifically targeted the digital bundles to the hallux, and specifically those to the sesamoids (Huang *et al.*, 1993; Murphy *et al.*, 1998; Thordarson *et al.*, 1997). This research may explain why, when sectioning the first digital bundle of the PA, the arch was not severely impacted (Chen *et al.*, 2014) and suggests that further research into musculotendinous and other soft tissue interactions of the first ray is needed.

Previous studies have found an inverse relationship between the thickness of the FHB and navicular drop, a measure of medial longitudinal arch height, finding that the FHB helped prevent navicular drop by contributing to maintaining the medial longitudinal arch, this suggests a connection to the plantar aponeurosis (Fukumoto *et al.*, 2020). The current study identified connections between the PA and the FHB heads (Figure 3.4.3), with connecting footprints and interdigitating fibres. The shared attachment zones between the FHB and the PA suggests a functional similarity. This concept is strengthened when considering similarities proximally. The proximal attachment of the FHB was indirectly anchored to the medial calcaneal tuberosity, via a diffuse, y-shaped, fibro-tendinous structure that attached into tarsal bones and into the medial intermuscular septum (Martin, 1964). Thus, the FHB mimics the PA in attachment sites, and perhaps functionally too.

The relationship of the FHL with the PA has been suggested via the formation of the entrance of the FHL tunnel (Haines *et al.*, 1954; Hedrick, 1996). This was confirmed in the current study, however, the observations made were that the PA formed a considerable proportion of the tunnel, especially proximally and dorsally (Figures 3.4.4 and 3.4.5). The plantar aspect of the tunnel was more diffuse in fibre direction, receiving contributions from the DTMTL laterally. However, the “transverse fibro-cartilaginous like ligament” observed in previous work (Kelikian *et al.*, 2011),

was made up of longitudinal fascicles from the plantar aponeurosis attaching distally into the distal phalanx. The current observations contend that the distal fascicles are less organised and more broadly interdigitated with surrounding tissues.

This research was not without limitations. The donors studied came from a sample population with a high mean age (82.1 years), which may be responsible in the differences in muscle morphology and occasional fascicle variation. The high age may lead to PA fascicles being smaller, thinner and/or weaker or indeed more diffuse. Comparisons with a younger sample population may provide more direct visualisations of the connections between tissues. The slight difference in footprint size on the HS has not been explained from the current data. Biomechanical studies of the relative strengths of the medial and lateral digital bands of the first ray independent of other fibrous tissues at the first MTPJ would clarify their functional capabilities. The combined dissection and digital modelling approach facilitated the detailed assessment of the PA in three dimensions and allowed for a reconstructive approach to visualising dissection data. Despite these advantages, the dissection process remains destructive. Future studies could include sectional analysis (macro-sections, histology, diceCT, etc.) to observe tissue interrelations with less investigative disruptions. Comparison data from these approaches would provide a more comprehensive account of the detailed anatomy. Within this study, only intra-observer variation was assessed, future studies can also include interobserver observation on key findings.

This research has outlined the extremely complex relationships of the distal PA at the hallux and mapped its footprints on the HS. This has helped clarify the individual roles of the fibrous tissues at the HS and first proximal phalanx and may help clinicians make more informed decisions regarding PA injury and function in forefoot deformities and conditions at the hallux. It may also encourage consideration of the broader functions of the PA when addressing hallux injuries.

3.4.5 References

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Part 4

Sectional Anatomy, Vasculature and Summary

Part Four, Chapter One

4.1 Sectional Anatomy of the Hallucal Sesamoid Attachments

4.1.1 Introduction

The use of fascicular dissection techniques was instrumental in identifying the many interactions and attachments of tissues to the hallucal sesamoids (HS). Irrespective of gains in reproducibility and decreased subjectivity, dissection is still destructive (Balcombe, 2001). Does this destructive process alter the interpretation of tissue interrelations? In order to confirm the reported observations in a manner that more closely approximates the *in situ* relations, a series of sectional studies were undertaken at macroscopic (macro-sections) and microscopic (histologic) levels.

In addition to potentially confirming dissection-based conclusions, a sectional approach may help conceptualise the structures of interest in the anatomical planes seen in medical imaging, such as MRI and CT (De Barros *et al.*, 2001). A sectional approach also highlights the morphological relationships between contiguous tissues *in situ*, enabling an accurate viewing of interconnected tissues without the need for them to be mechanically separated from one another (Cook *et al.*, 1997). Macro-, or thick-, sections enable two-dimensional views of large areas of tissue with minimal preparation.

The attachments of the tendons and ligaments to the HS were observed during dissection and mapped using a digital microscribe, however, the nature of the attachments was not always clear. Attachment to bone was implied in most cases, whereas in others, it was unclear whether the tissue attached to bone, or merely passed close the bone, merged with other attachments, or terminated in other adjacent soft tissues (e.g., joint capsule). From a functional perspective, determining whether the attachments were enthesial, as in forming a true, mechanically-significant attachment to the bone (Benjamin *et al.*, 2006) may be important. An enthesis is the transformation of fibrous tissues, such as ligament and tendon, into a specialised unit, with the reciprocal bone, at the site of skeletal attachment. Representing focused, directional mechanical transfer of force to the attachment site (Benjamin *et al.*, 2006), and enthesis is essentially the blending of flexible, mobile fibrous tissues (ligament, tendon), into relatively firm, immobile (and therefore more mechanically absorptive) bone, with the former increasingly calcifying as it approaches the latter. If attachments observed through dissection can be verified histologically as enthesial, a stronger case for their functional/mechanical significance can be made. Whilst dissection, especially under magnification, allows some degree of confidence in determining attachment of tissues, and macro-sections allow the same tissues to be observed closer to their *in situ* arrangement, neither provide non-subjective differentiation of tissue. Histology not only allows for thinner sections and hence more highly magnified visualisation of the tissue, but also allows for specialised differentiation of tissues through the employ of specific stains. Staining for the histologic assessment of ligaments and

entheses has previously been optimised (Al Saffar, 2016; Fogg, 2004) with a specially Modified Masson's Trichrome procedure. Complemented by an optimised decalcification and embedding protocol (Al Saffar, 2016; Fogg, 2004), this approach will allow clear visualisation and differentiation of the tissues around, and attaching to, the hallucal sesamoids.

Given the world-wide public health crisis in 2020 and 2021, access to central facilities for these sectional processes was limited. Rather than a detailed account of each of the dissected structures, the sectional data will be presented as a pilot study for the comprehensive validation of dissection-based data and the sectional visualisation of the first ray. In this context, this study aims to demonstrate the value of sectional anatomy at both macroscopic and microscopic levels.

4.1.2 Material and Methods

Macro-sections

Macro-sections were created using multiple methodologies to optimise tissue visualisation. A variety of preparatory approaches were tried in order to establish an ideal protocol for future studies.

The first technique used was that of frozen specimen band sawing. Embalmed (Anatomical Series, Genelyn, Australia; see Appendix 5.1) Body Donor feet (n= 10; female = 6, male = 4; mean age = 84.9 years), not previously dissected that had no obvious visible morphological oddities or known surgery or pathologies. Selected feet were frozen at -80C over a 48-hour period. Each foot was taken directly from the freezer for cutting, with minimal time delay and no additional processing. Sections were cut with a bandsaw (Barnes Blademaster MK1, HT Barnes, Sydney, Australia) to a thickness of 3 mm in either a coronal (n = 6) or sagittal plane (n = 4; see Appendix 5.12).

The second macro-section method was done in conjunction with a decalcification step. Embalmed (Anatomical Series, Genelyn, Australia; see Appendix 5.1) Body Donor feet (n= 5; female = 2, male = 3; mean age = 82.7 years) were cut to size to include the first and second rays and their associated tissues. The resultant macro block was then decalcified, after which the specimen was embedded in gelatin, paraffin or polyurethane and

cut into 1-2mm sections in a given plane (1 sagittal, 1 transverse and 3 coronal) using a commercial slicing device (VEVOR 300mm Slicer, VEVOR, USA); (see Appendix 5.13).

All resultant sections were cleaned and photographed (EOS 5D mark III, Canon, Japan) on both sides, backlit by an x-ray lightbox.

Histologic Sections

Embalmed (Anatomical Series, Genelyn, Australia; see Appendix 5.1) Body Donor feet (n= 9, female= 6, male= 3; mean age= 79.85), not previously dissected, were frozen at -80C over a 48-hour period. Each foot was taken directly from the freezer for cutting, with minimal time delay and no additional processing. Specimen blocks were cut with a bandsaw (Barnes Blademaster MK1, HT Barnes, Sydney, Australia; see Appendix 5.12) to reduce the amount of tissue to be subject to further processing, and to provide a sectionable block that included as little non-target tissue as possible.

The histologic processing (decalcification, embedding, perfusion, sectioning and staining; see Appendix 5.14) was tested against existing, specialised protocols (Al Saffar, 2016; Fogg, 2004). The resulting slides were photographed for digital assessment.

4.1.3 Results

Macro-sections

The results of the macro-section pilot study are presented with coronal sections (Figures 4.1.1 to 4.1.2) and sagittal sections (Figures 4.1.3 to 4.1.6), highlighting the key observations in relation to the dissection-based studies.

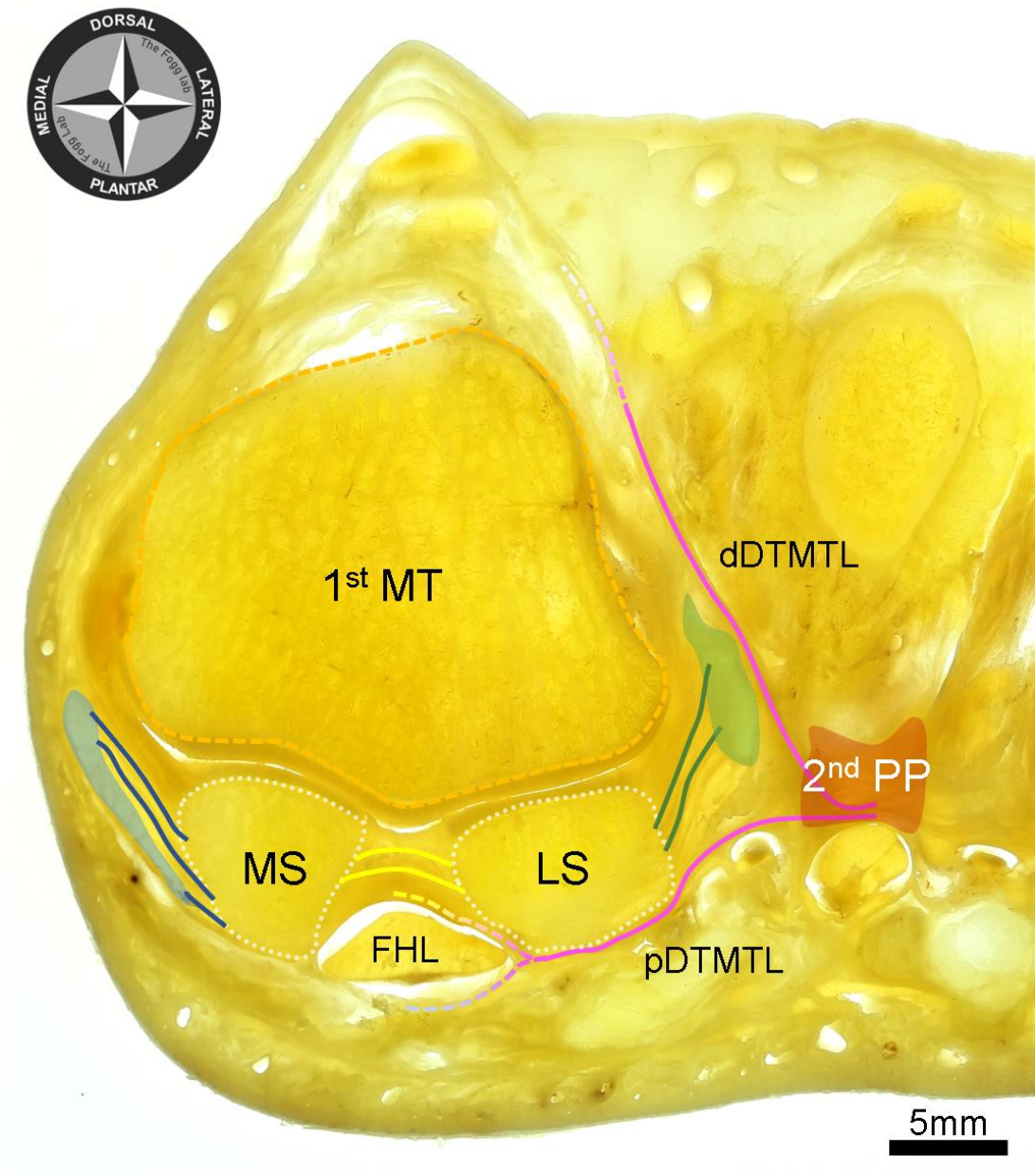


Figure 4.1.1. A Coronal section at the level of the medial (MS) and lateral (LS) hallucal sesamoids (white dotted lines), and the first metatarsal (1st MT, orange dashed line) head. Laterally from the second plantar plate (2nd PP, red shadow) the deep transverse metatarsal ligament extended out dorsally (dDTMTL) and plantarly (pDTMTL) to reach the extensor tissues and the lateral sesamoid /flexor hallucis longus (FHL) tunnel respectively. The medial aspect of the MS received fibres from the abductor hallucis (blue lines) and its conjoint tendon (blue shadow). The lateral aspect of the LS received fibres (green lines) from the conjoint tendon of the adductor hallucis (green shadow).

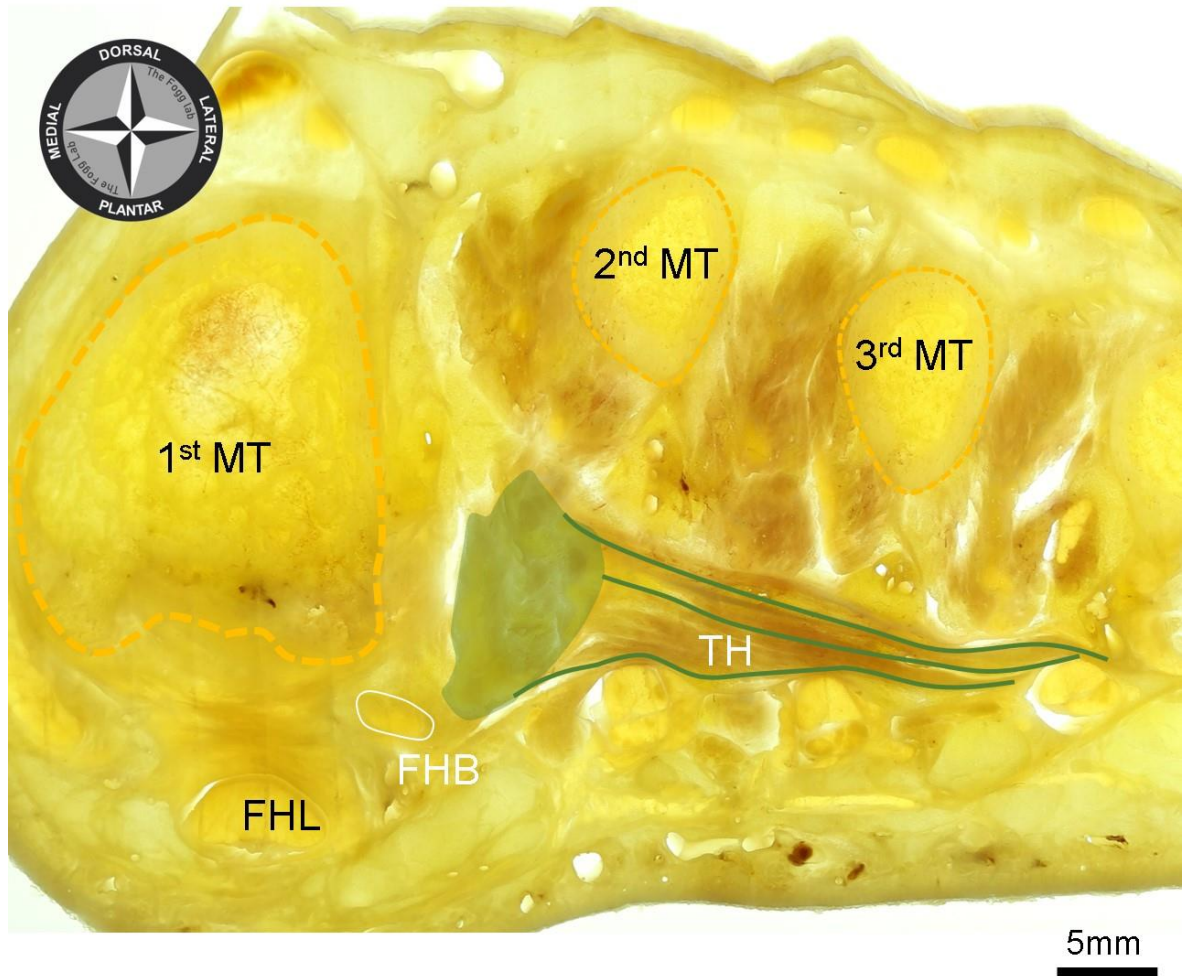


Figure 4.1.2. A coronal section of the forefoot at the level of the first metatarsal (1st MT) neck centred at the second (2nd MT) and third (3rd MT) metatarsals. Following the fibres of the transverse head (TH, green fibres) of the adductor hallucis medially to its interdigitation into the adductor conjoint tendon (green shadow) before reaching the lateral sesamoid, along with the tendon of the flexor hallucis brevis (FHB, white outline). Flexor hallucis longus (FHL).

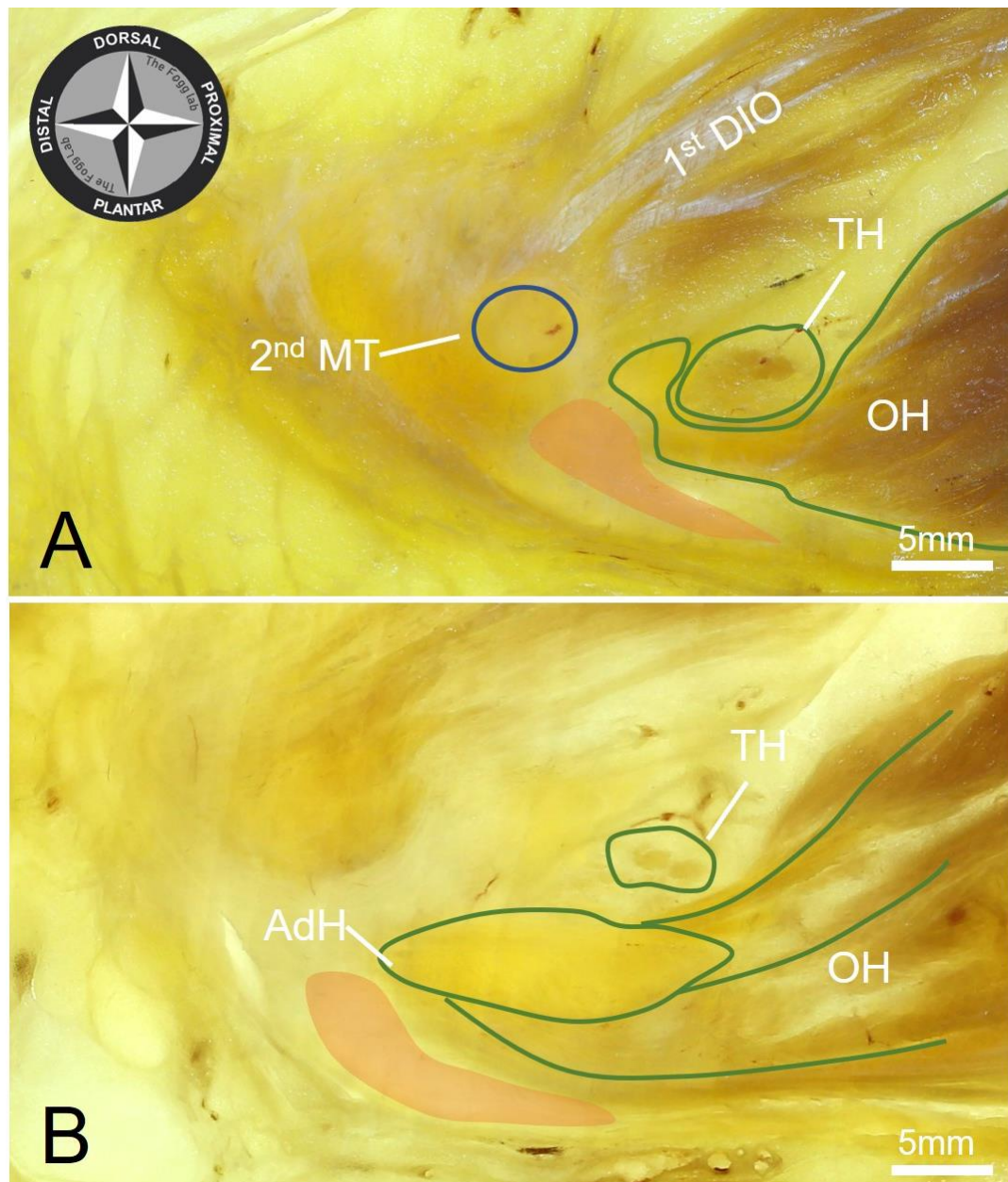


Figure 4.1.3. A sequence of sagittal sections centred at the metatarsal heads, at the level of the first webspace between the first and second (2nd MT, blue outline) metatarsals. A- The lateral tubercle of the second metatarsal, was being closely passed by the first dorsal interosseous muscle (1st DIO), plantar to which the transverse head (TH) and oblique (OH) heads of the adductor hallucis ran medially, alongside a body of fibrous tissue, the deep transverse metatarsal ligament (pink shadow) from the second plantar plate. B- A more medial section showing the convergence of the adductor heads into the adductor hallucis (AdH) conjoined tendon. *Figure continues on the next page.*

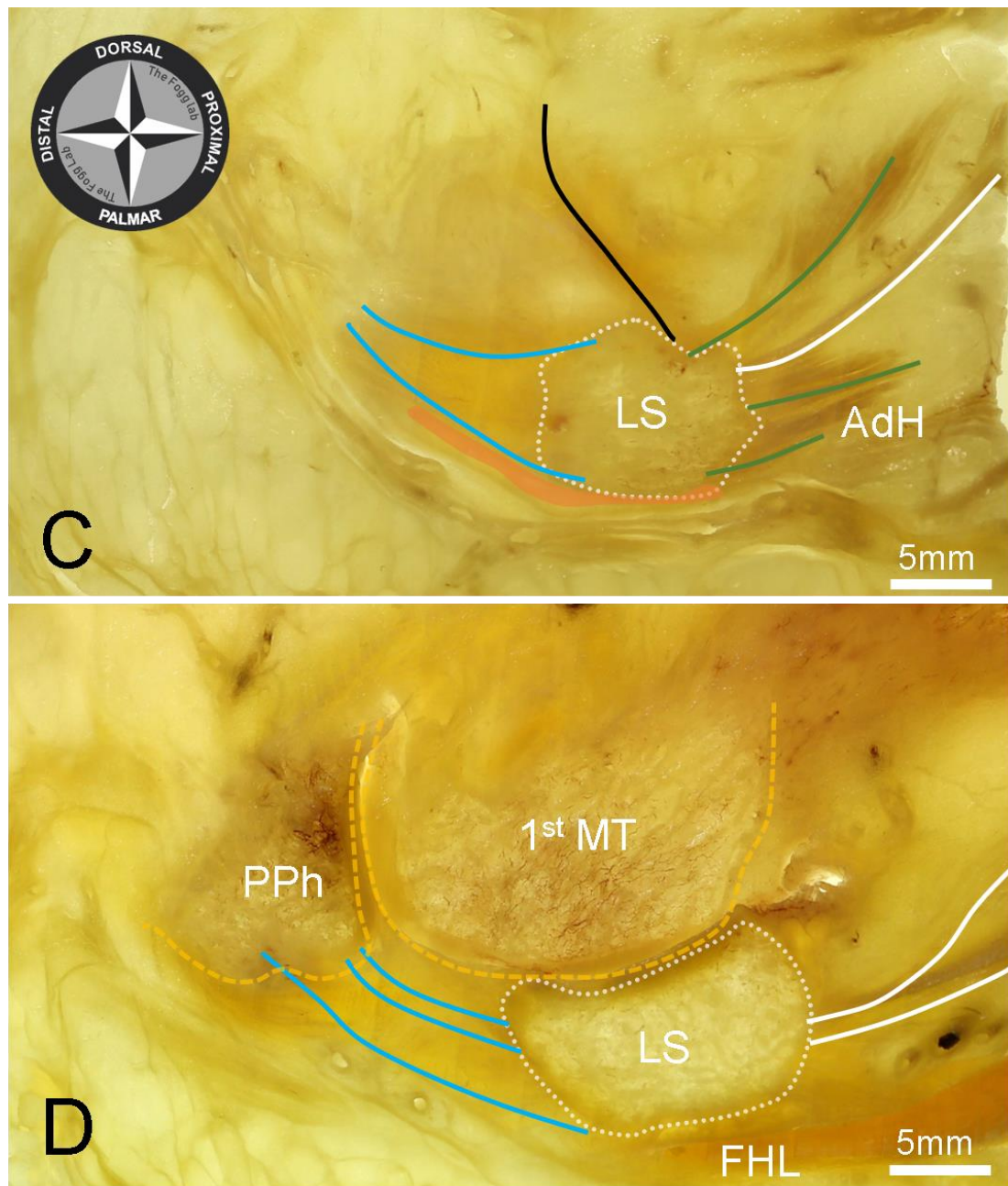


Figure 4.1.3. *continued*. The continued sequence of sagittal sections centred at the metatarsal heads at the level of the lateral sesamoid (LS). C- The lateral aspect of the lateral sesamoid (white dotted line) is shown at the endpoint of the medial journey taken by the adductor hallucis fibres (AdH, green lines), and the deep transverse metatarsal ligament (pink shadow) on the plantar aspect of the LS. Additional interactions are noted such as the fibres from the flexor hallucis brevis (white line) and the lateral metatarsosesamoid ligament (black line) connecting the LS to the first metatarsal (1st MT) head. Distally the lateral sesamophalangeal ligaments (cyan lines) connect the LS to the proximal phalanx (PPh). B- A section medial to C, showing the relationships with the PPh and 1st MT more clearly, as well as the incoming flexor hallucis brevis and flexor hallucis longus (FHL).

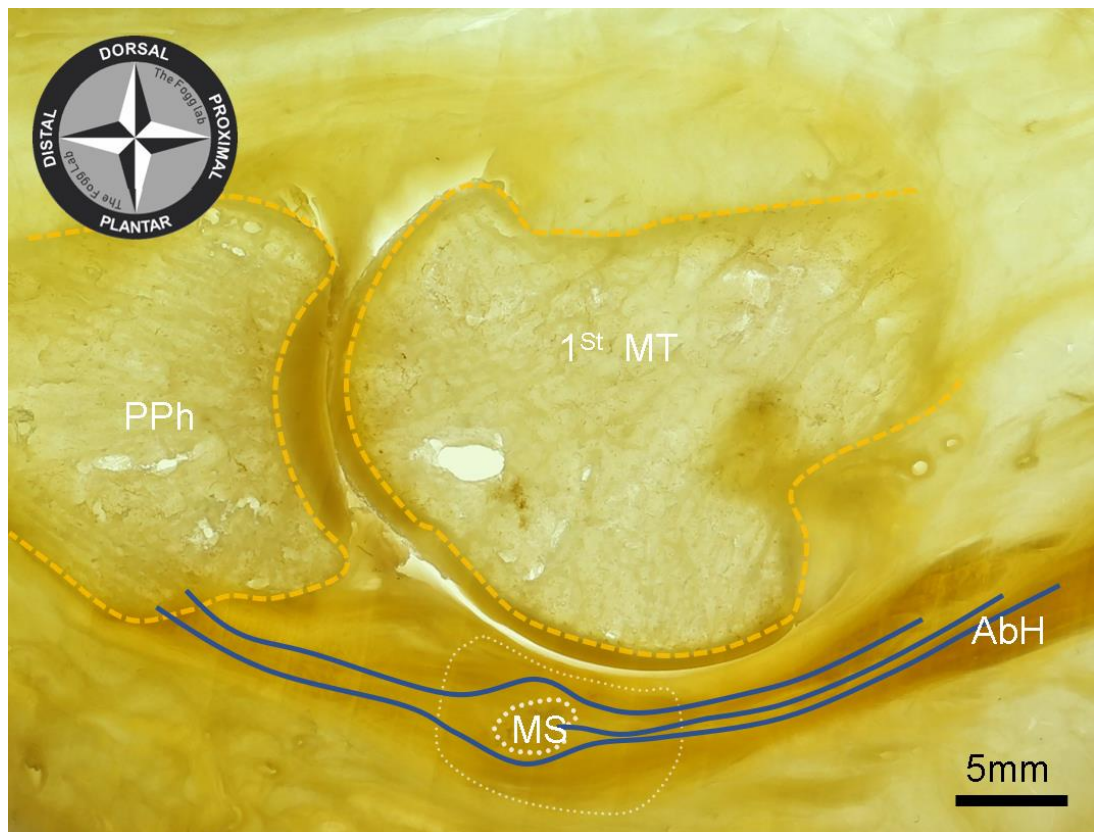


Figure 4.1.4. A sagittal view of the medial aspect of the first metatarsal (1st MT) head and proximal phalanx (PPh), showing the superficial most fibres of the abductor hallucis (AbH, blue lines) bypassing and connecting to the medial sesamoid (MS, larger white dotted line) and its medial most cut surface (smaller white dotted line circle).

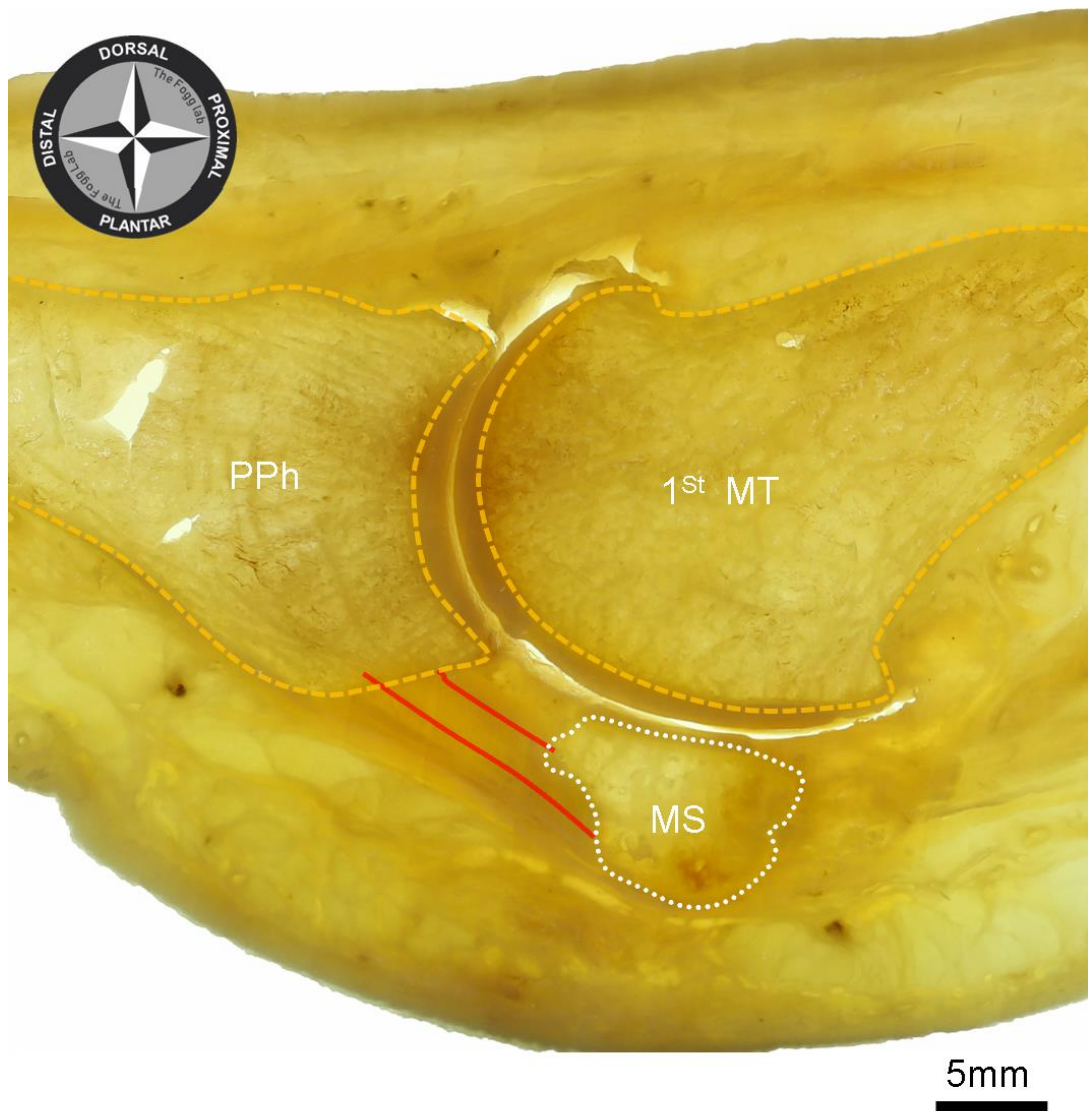


Figure 4.1.5. A sagittal section centred at the first metatarsal (1st MT) and proximal phalanx (PPh) and their interactions with the medial sesamoid (MS), white dotted line), highlighting the strong fascicular tissue of the medial sesamophalangeal ligament (red lines).

Histologic Sections

The results of the histological pilot study are presented in Figures 4.1.7 to 4.1.8. These figures also demonstrate the range in staining success, as part of optimising the protocol to locally available solutions and local equipment calibrations. This step is always essential with each region studied (Al Saffar, 2016; Fogg, 2004), as it also accounts for differences in embalming protocols, individual Body Donor reaction to embalmment and the histologic processing and the varying density of tissues in the block, e.g., a block with many articular surfaces and only capsular structures acts quite differently to a block with large tendons and fewer articular surfaces (Fogg, 2004).

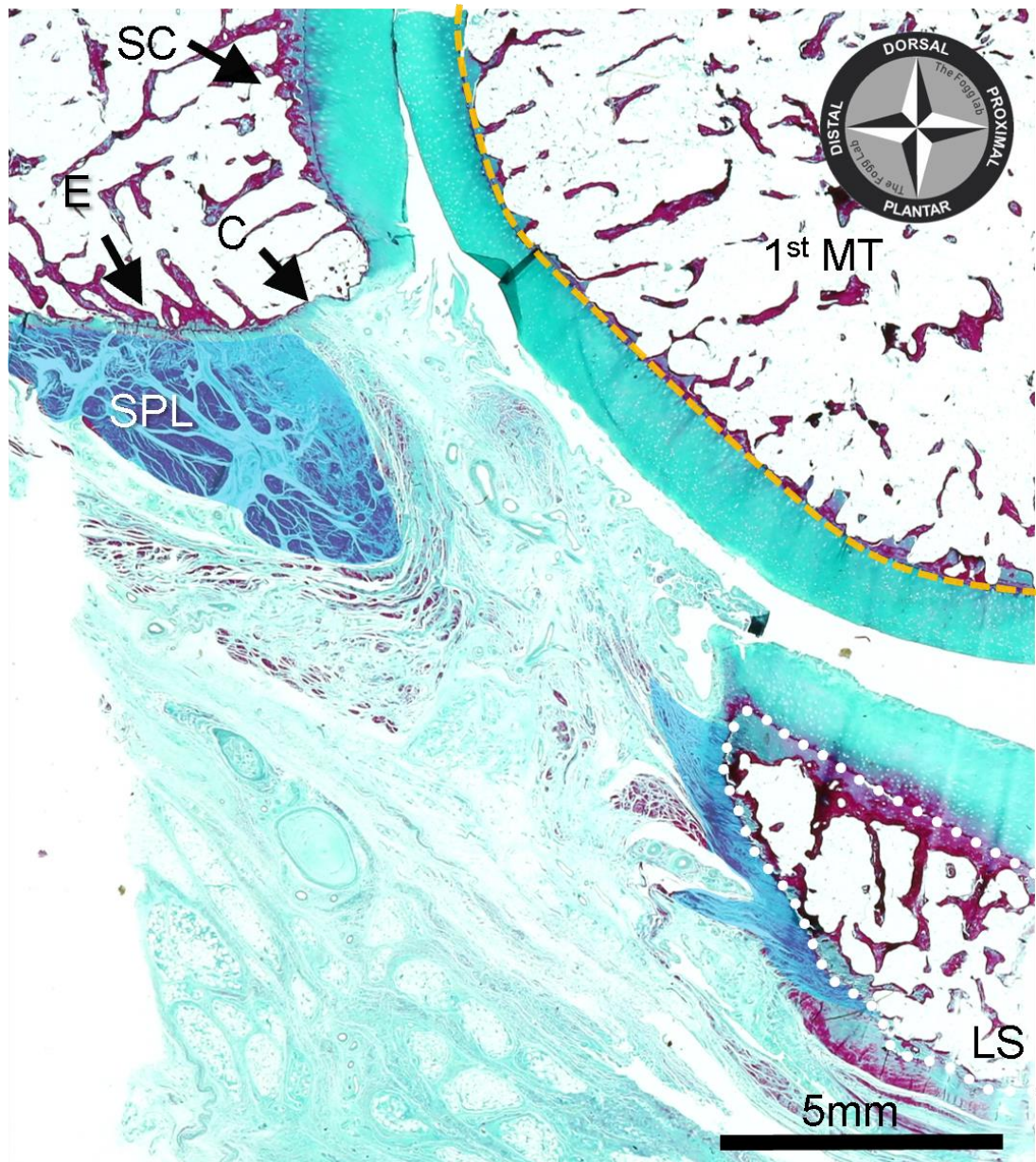


Figure 4.1.6. A sagittal histological section at the level of the lateral sesamophalangeal ligament (SPL, blue shadows), connecting the lateral sesamoid (LS) with the proximal phalanx, the oblique fibres are seen attaching to the base of the proximal phalanx. At an enthesial attachment (E) showing thick cortical bone with a fibrocartilaginous tidemark and thick trabeculae, suggesting a mechanically significant attachment, compared to the capsular attachment (C) with very thin cortical bone, beside the subchondral bone (SC) interacting with forces against the first metatarsal (1st MT) head. Modified Masson's Trichrome, magnification x3.

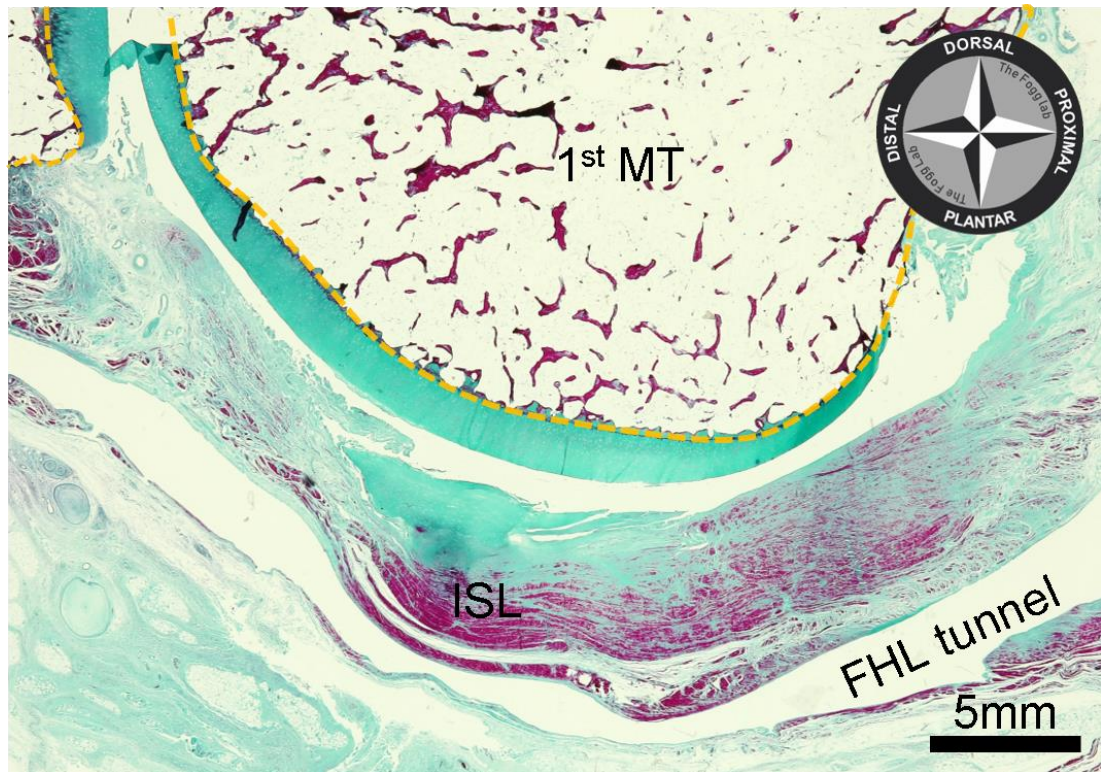


Figure 4.1.7. A sagittal histological section at the level of the intersesamoid ligament (ISL) with its transversely oriented fibrocartilage rich fibres sitting plantar to the first metatarsal (1st MT) head and dorsal to the flexor hallucis longus (FHL) tunnel lined with smooth fibrocartilaginous tissue along its length. Modified Masson's Trichrome, magnification x3.

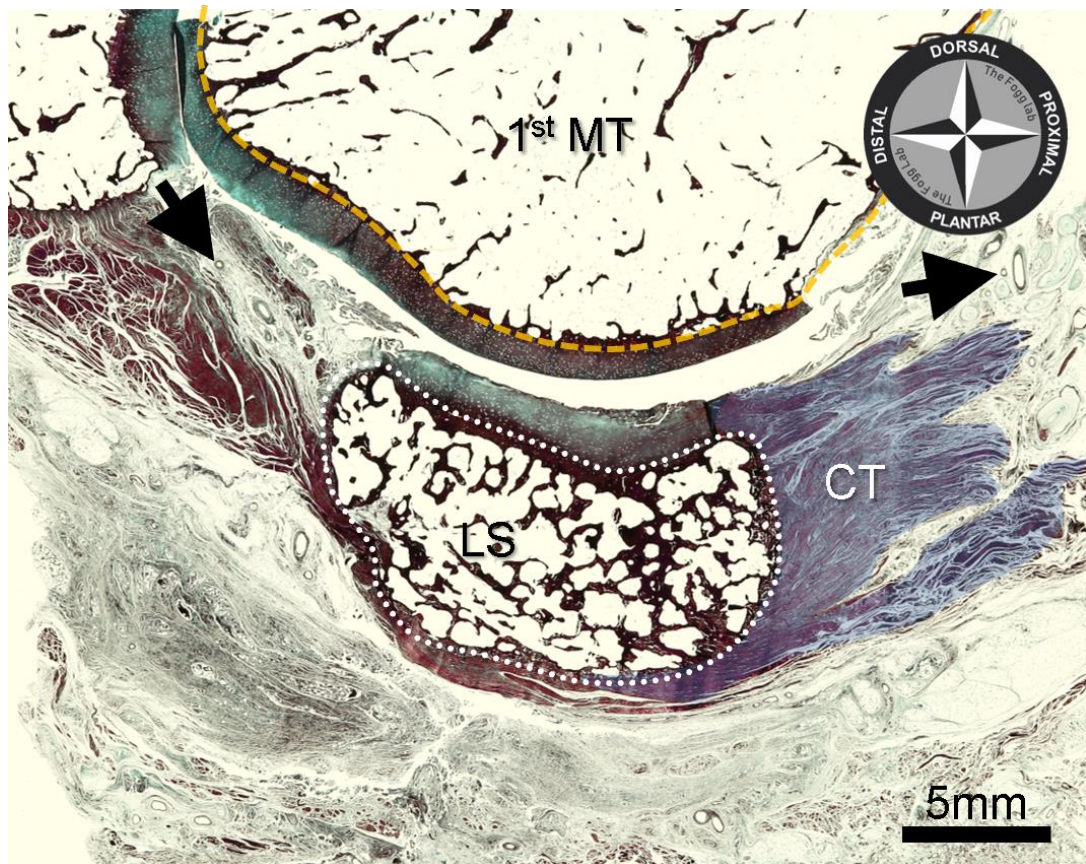


Figure 4.1.8. A sagittal histological section at the level of the lateral sesamoid (LS, white dotted line) and the first metatarsal (1st MT) head, highlighting the mass of conjoined lateral tendons (CT, blue shadow) attaching into the proximal pole of the LS at entheses. Histology permits the visualisation of blood vessels and their relationships to these hallucal sesamoid attachments (black arrows). This section is representative of poorly optimised staining. Due to a variety of individual tissue, individual Body Donor and procedural differences, this staining protocol requires optimisation for every sample. Modified Masson's Trichrome, magnification x3.

4.1.4 Discussion

The sectional images presented served two purposes successfully. Firstly, the macro-sections demonstrated that the fascicular dissection process employed in previous chapters did not erroneously alter relationships between tissues. Whilst the dissection and digital modelling approach provided excellent visualisation of attachment footprints and some spatial relations, the macro-sections augmented those findings with imagery more akin to medical sectional imagery (CT and MR images).

Whilst successful and useful for the demonstration of planar *in situ* relations, the macro-sections were limited by their two-dimensionality and lack of tissue differentiation. Three-dimensional relations were well-depicted through the combination of dissection and digital modelling, so the combination of these three modalities is recommended for thorough analyses of anatomical relations. Tissue differentiation in macro-sections may be addressed in subsequent studies, where the application of combinations of diaphanisation (tissue clearing), decalcification, macro-staining and contrast-enhanced CT/ μ CT have been tried but, primarily due to COVID-19-induced delays, restrictions and facility closures, are yet to produce viable results. It is hoped that future success with these trials will establish a rigorous, multi-modal series of protocols that can be employed in any subsequent studies. The thickness of the macro-sections was limited by the equipment available, 1-2mm would have been preferred, however 3mm was what could realistically be achieved and as such more specimens were required to

observe this dense anatomical area using this technique. New techniques for thinner macro-sections are currently in development.

Secondly, the histologic sections demonstrated that the major attachments observed in the dissections were enthesial. These sections confirmed the assertion that the majority of the non-articular surface of the hallucal sesamoids is for soft tissue attachment, and that these attachments are likely to be mechanically significant. The mechanical nature of these entheses was emphasised by the visibly thicker enthesial bone, compared with the moderately thick subchondral bone and the particularly thin capsular (non-enthesial) bone. A more comprehensive range of sections would warrant quantitative assessment of the area of each of these bone types. Previous studies (Al Saffar, 2016; Fogg, 2004) have demonstrated statistically significant areas between these bone types, indicating a clear functional difference. Future HS studies will aim to document each attachment histologically to provide comprehensive validation of the dissection-based findings.

The histologic sections also demonstrated neurovascular relations to the tissues converging on the HS. These structures were under-reported in the reviewed literature. Damage to vasculature in this area is associated with avascular necrosis of the HS (Pretterklieber *et al.*, 1992), so an understanding of the vascular relations to the HS, and especially to those structures targeted surgically in procedures like hallux valgus release, may provide an anatomical basis for long-term implications of tissue damage. In

addition to the histologic sections, the vascular relations will be briefly explored in the subsequent chapter.

Sectional studies provide valuable information that complements, but does not replace, dissection-based data. This pilot study has demonstrated the importance of sectional images when considering the detailed anatomy of the first ray, supporting the inclusion of sectional data in any further comprehensive studies of this area. This study has also established clear, reproducible protocols that will enable other studies to produce comparable results, or to apply these approaches elsewhere in the body.

4.1.5 References

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Part Four, Chapter Two

4.2 The Nutrient Arteries of the Hallucal Sesamoids

4.2.1 Introduction

There are numerous painful conditions at the first metatarsophalangeal joint, of these conditions avascular necrosis of the hallucal sesamoids (HS) is a relatively common occurrence as the sesamoids are vulnerable to such vascular insults (Karasick *et al.*, 1998; Pretterklieber *et al.*, 1992; Sims *et al.*, 2014). Idiopathic avascular necrosis of the HS is rare, but poorly understood (Bartosiak *et al.*, 2019; Fleischli *et al.*, 1995; Ogata *et al.*, 1986; Toussirot *et al.*, 2003), and there is also an iatrogenic risk of developing avascular necrosis of the HS during surgery to treat disorders such as hallux valgus (Berkowitz *et al.*, 2019). The accidental disruption to the arterial supply of the HS from lateral approaches to the lateral sesamoid or plantar approaches to both sesamoids was suggested as a potential cause of post-operative pain (Pretterklieber *et al.*, 1992). Excessive bone stripping and disruption of the more proximal blood supply whilst carrying out first metatarsal osteotomies can adversely affect the nutrient arteries to both the first metatarsal head and the hallucal sesamoids (Pretterklieber *et al.*, 1992). During hallux valgus correction surgery, the often accompanying process of lateral soft tissue release has been shown to be insufficient and damaging to surrounding structures at the lateral border of the lateral sesamoid (Lin *et al.*, 1996), which could very easily damage the lateral sesamoid nutrient artery (Pretterklieber *et al.*, 1992).

In reported cases of idiopathic avascular necrosis, pain plantar to the affected HS and an inability to walk on the affected area usually preceded any radiographic evidence by six months (Bartosiak *et al.*, 2019; Toussirost *et al.*, 2003). Acute post-operative identification of such issues may therefore be unlikely, suggesting the need for more a targeted performance and pain scoring tool to address this issue. Improved knowledge of the arterial supply of the hallucal sesamoids is crucial in better understanding the causative agents of both traumatic and idiopathic conditions and could inform surgical decision-making in this area. This may reduce the incidence of post-operative HS avascular necrosis.

Disorders of the first ray may also be linked to habitual loading, and particularly that enforced by shoe choice. Calcific tendinosis around the first metatarsophalangeal joint (MTPJ) has a propensity to occur in young women, representing up to 79% of cases (Garner *et al.*, 2013). The habitual wearing of high heeled shoes with a narrow toe box are associated with increased incidence of forefoot abnormalities such as metatarsalgia, Civinini-Morton syndrome, Freiberg infraction, hallux valgus, callosities and hallux rigidus (Colò *et al.*, 2021; McBride *et al.*, 1991). The influence of long-term extreme loading on the HS is unclear. It may contribute to skeletal adaptations, be a cause of microtrauma and may influence vascularity and sensation of the region (Martin Oliva *et al.*, 2020; Pretterklieber *et al.*, 1992). Better understanding of the influence of foot posture on HS loading, and of the neurovascular relations of the HS, may present an anatomical rationale

for the development of these disorders. This may inform diagnosis and treatment strategies and may also inform public health guidance.

This pilot study aims to explore means of visualising HS load and vasculature. This may provide a basis for future, more detailed studies.

4.2.2 Materials and Methods

Feet from embalmed (Genelyn Anatomical Series, Australia; see Appendix 5.1) Body Donors (n = 16; female=9, male= 7; mean age = 84.64 years) were examined in accordance with *Part IV of the Human Tissue Act (1992)* and with local ethics approval (project ID: 12292). Exclusion criteria included any signs of previous surgery, or obvious, visual hallux valgus or previously diagnosed diabetes mellitus or peripheral vascular disease from medical notes. The feet were CT scanned with a Siemens Biograph 128-slice ultraHD-PET CT scanner (Siemens, Germany; see Appendix 5.11). From these, suitable feet (n= 14; female= 7, male= 7) were selected to undergo microvascular injection (see Appendix 5.15).

The selected specimens were prepared for microvascular injection, by placing a cannula into the posterior tibial artery in all specimens as it had a consistently large gauge and is identified to supply the majority of the plantar foot. The anterior tibial artery and fibular artery were cannulated when possible. A warm contrast solution of Barium Sulphate (30%) and Gelatin (10%) was injected into the feet with a peristaltic pump (Cole-Parmer Masterflex® Peristaltic pump 7553; see Appendix 5.15). The feet were then checked for adequate perfusion with plain radiographs (Figure 4.2.1; see Appendix 5.10). The well perfused feet were then sent to be CT scanned again with a Siemens Biograph 128-slice ultraHD-PET CT scanner (Siemens, Germany; see Appendix 5.11).

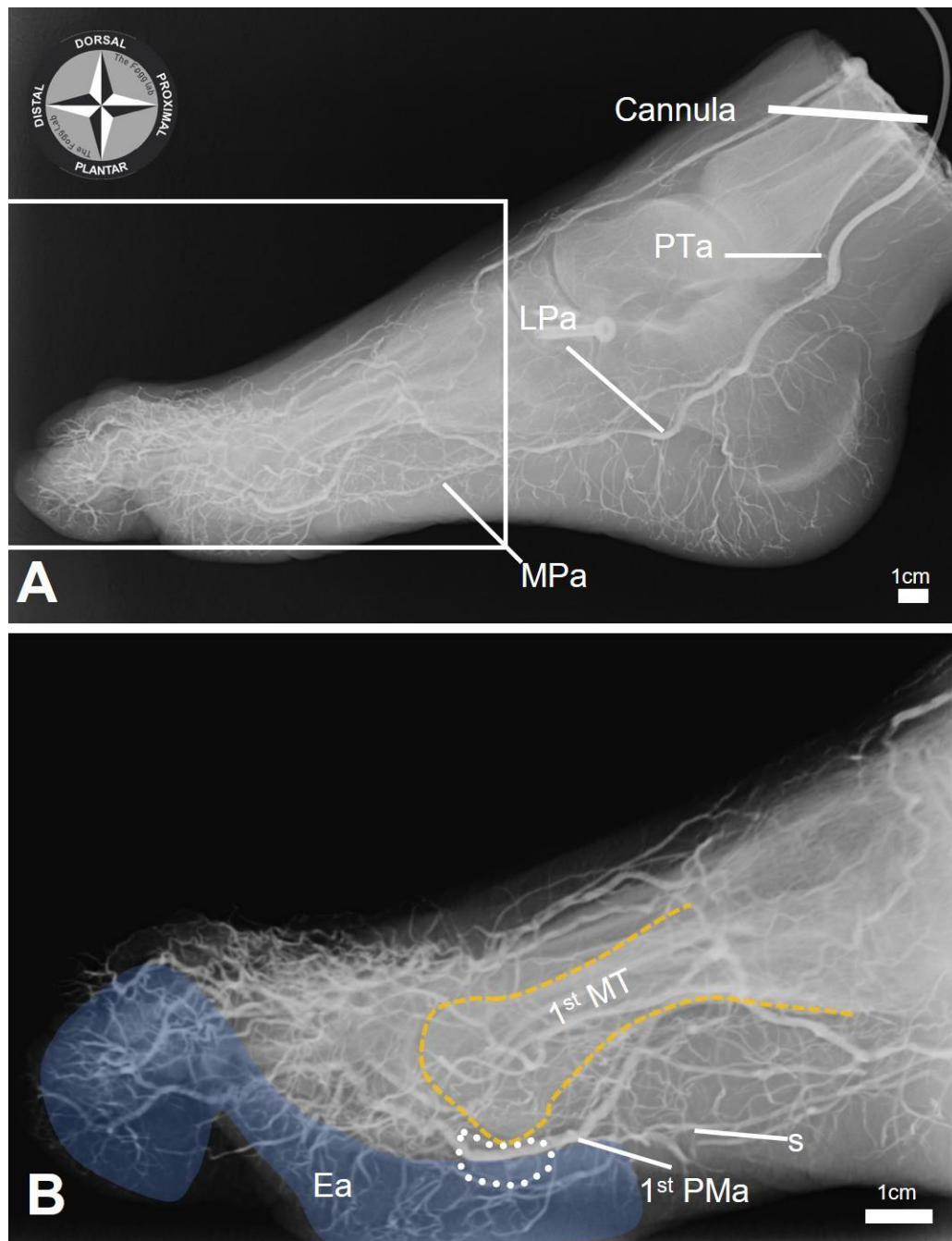


Figure 4.2.1. A lateral projection X-ray of a well perfused micro-vascular injected foot. A - A view of the whole foot, demonstrating the cannulation of the posterior tibial artery, flowing from which the contrast has reached the medial plantar artery and the lateral plantar artery (LPa). B - A close up of the white box contents in A, showing the small gauge of the arteries reached distally, seeing the formation of the first plantar metatarsal artery (1st PMA) as well as a superficial branch of the medial plantar artery (s), which all reached into the hallual sesamoids (white dotted line), the first metatarsal (1st MT, yellow dashed line) and the end arteries (Ea, blue shadow) of the toes.

Feet displaying excellent contrast perfusion were then prepared for micro CT scanning (n= 5; female= 2, male= 3). These feet were cut into blocks no larger than 50mm by 50mm to suit the field of view of the machine.

Selected feet (n= 2; female= 1, male= 2; mean age of 69 years), were further processed for contrast enhanced micro-CT scanning (see Appendix 5.4) to visualise the relationships of the vascular anatomy at the hallux with the soft tissues to the hallucal sesamoids.

Weight bearing CT scans were carried out on a single right foot (n =1; male; age = 30 years) with differing parameters (see Appendix 5.16), such as footwear (barefoot and heeled shoes), and heel height (0cm, 50mm, 100mm and 130mm). The resultant scans were then measured and compared.

4.2.3 Results

The CT scans provided bony data and further signs of previous surgery and bony deformities. Alongside the plain radiography, CT data was used to determine partism within the specimens; no partism was found within the scanned specimens. With the addition of contrast into the arteries, the CT-scanning and plain radiography enabled visualisation of vessels to the hallucal sesamoids (HS), but the resolution on the CT scanner was insufficient to visualise the course of the blood vessels directly into HS. The main vascular sources could be observed from the posterior tibial artery into the medial tibial artery into its superficial and deep branches towards the HS (Figures 4.2.1. and 4.2.2.), but the details were lost closer to the HS. The use of micro-CT scanning allowed the visualisation of finer vessels reaching the HS as well as the nutrient foramina on the sesamoidal surfaces (Figures 4.2.3, 4.2.4 and 4.2.5). Arteries were observed reaching the proximal poles of the HS entering the proximal nutrient foramina of all contrast injected micro-CT scanned specimens. Arteries were seen projecting plantar to the HS in a couple of cases of the CT scans (n=2; 40%; Figures 4.2.4 and 4.2.5). The contrast enhanced soft tissue micro-CT scans identified soft tissues interacting with the HS (Figure 4.2.5B) and the position of the nutrient foramina within these attachments on the proximal poles.

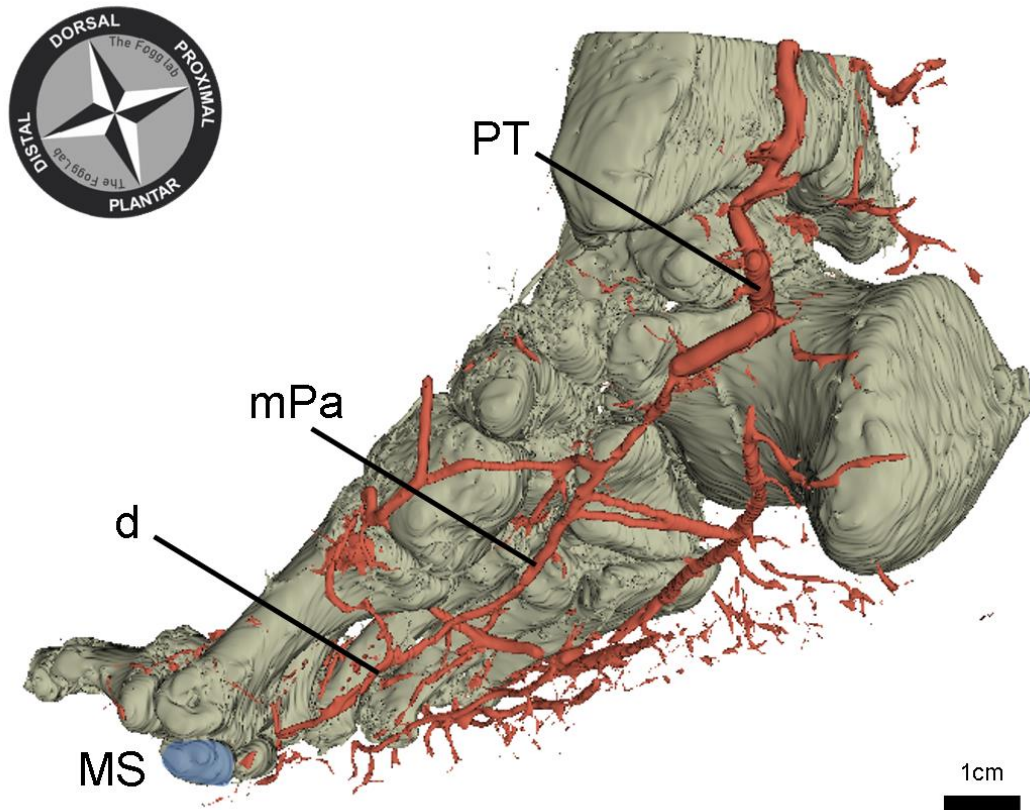


Figure 4.2.2. A proximal medial view of CT scan segmentation of a right foot after contrast injection, highlighting how the arteries (red) approached the medial sesamoid (MS, blue shadow) From the posterior tibial artery (PT) proximally, the medial plantar artery (mPa) continued distally to branch into a deep branch (d) that reached the hallucal sesamoids.

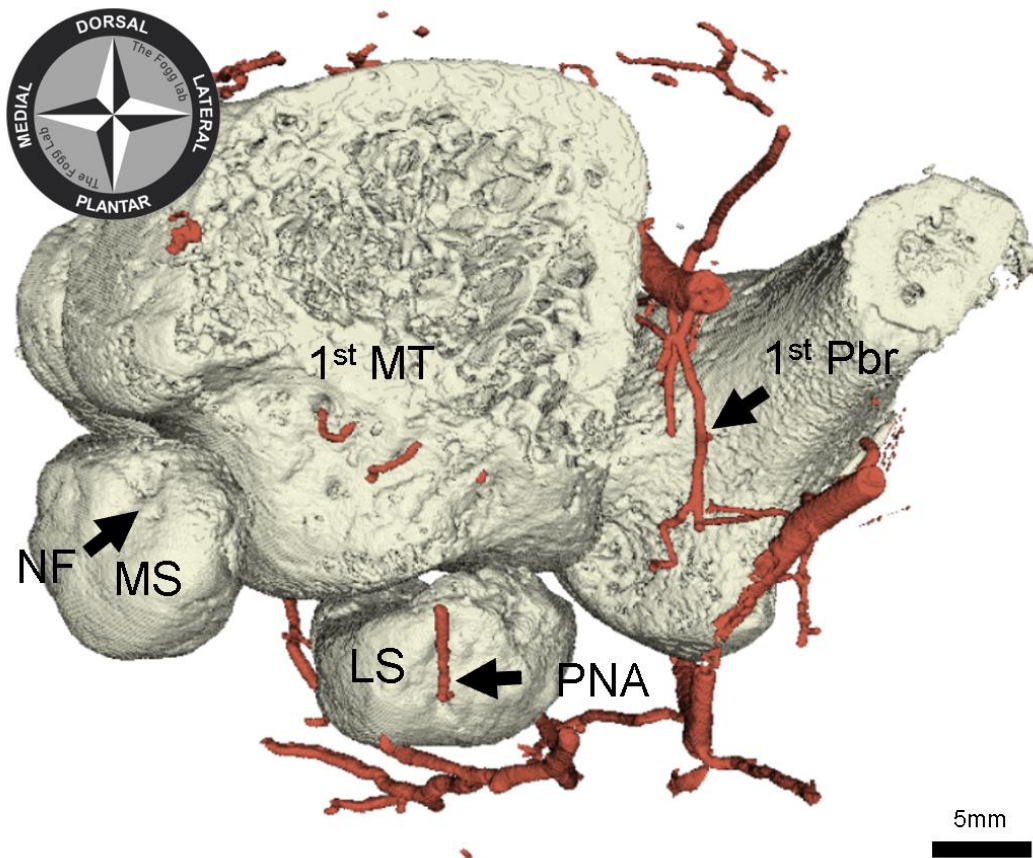


Figure 4.2.3. A posterior view of a micro-CT scan segmentation of the right first metatarsal (1st MT) and second ray with the contrast injected arteries (red) that connected into the lateral (LS) and towards the medial (MS) hallucal sesamoid. The arteries in view were the proximal nutrient artery (PNA) to the LS that reached the proximal nutrient foramen of the LS, and the nutrient foramen of the MS (NF) was observed proximally. From the first dorsal metatarsal artery the first perforating branch (1st Pbr) can be seen in the first webspace.

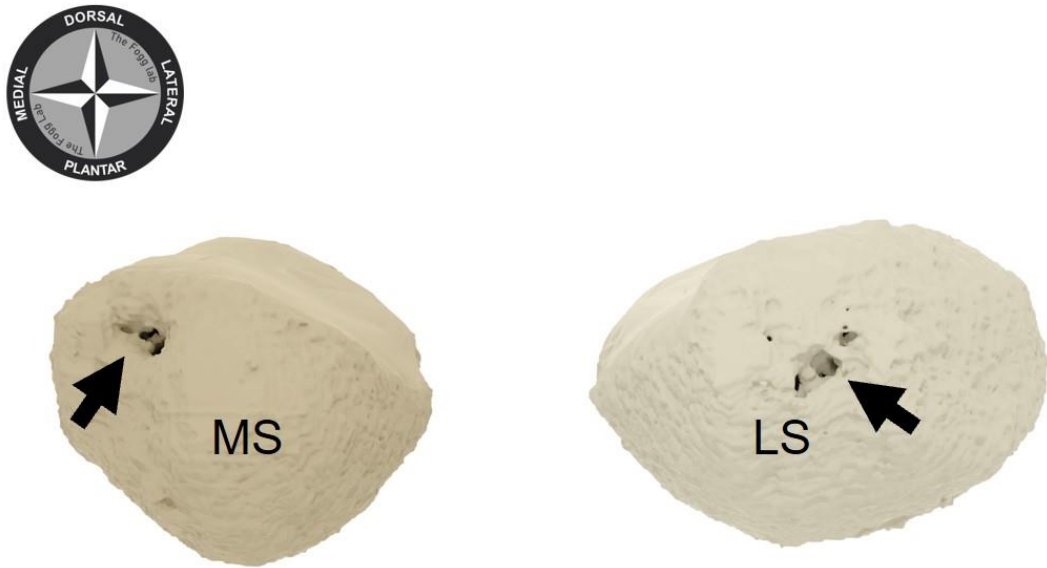


Figure 4.2.4. A proximal view of the medial (MS) and lateral (LS) sesamoids, in position, reconstructed from micro-CT scan segmentation. Highlighting the significant proximal nutrient artery foramina (black arrows).

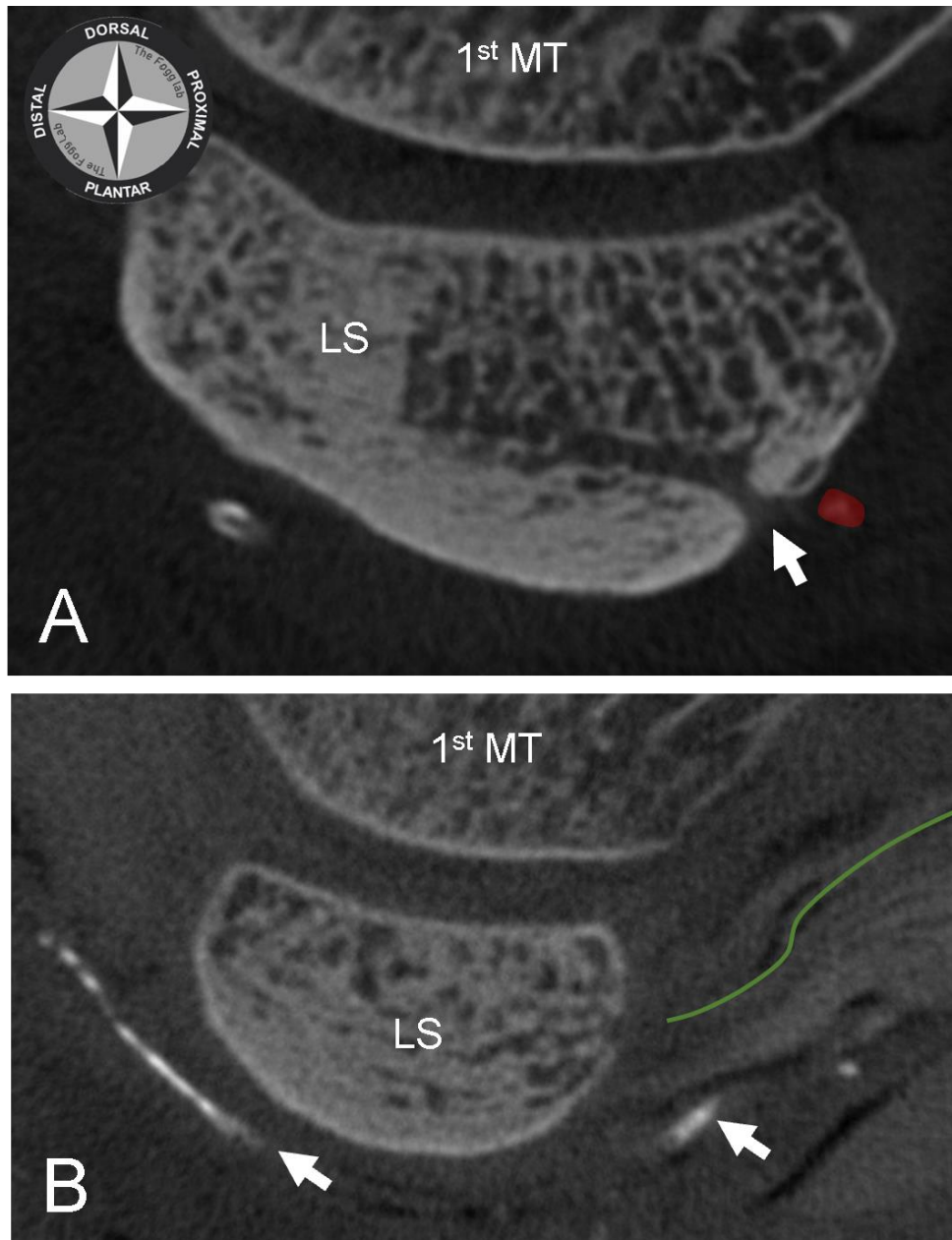


Figure 4.2.5. Sagittal views of and a lateral (LS) sesamoid from two micro CT reconstructed and resliced datasets. A - The proximal pole of this LS showed a very large nutrient foramen (white arrow) with a nutrient artery (red shadow). B - A contrast enhanced specimen using iodine, it highlighted the visualisation of fascicles from the adductor hallucis (green line), plantar to these LS, arteries were visualised (white arrows). The thickness of the cortical bone and cancellous arrangement could be visualised with the use of micro-CT.

The weightbearing CT scans (Figure 4.2.6) revealed that, throughout the range of motion of added heel height, the distance between the HS and their respective proximal phalanx tubercles was always the same, suggesting no stretching of the sesamophalangeal ligaments. The metatarsal head rotated inwards (pronated) with heel lift. The tighter toe box of the heeled footwear reduced the splaying at the transverse arch of the foot and brought the distal phalanges together, creating a “claw-like” effect on the phalanges of the lesser toes. The angle of the ground reaction force through the first metatarsal was suggested to move from the proximal phalanx to the distal pole of the HS with increasing heel height.

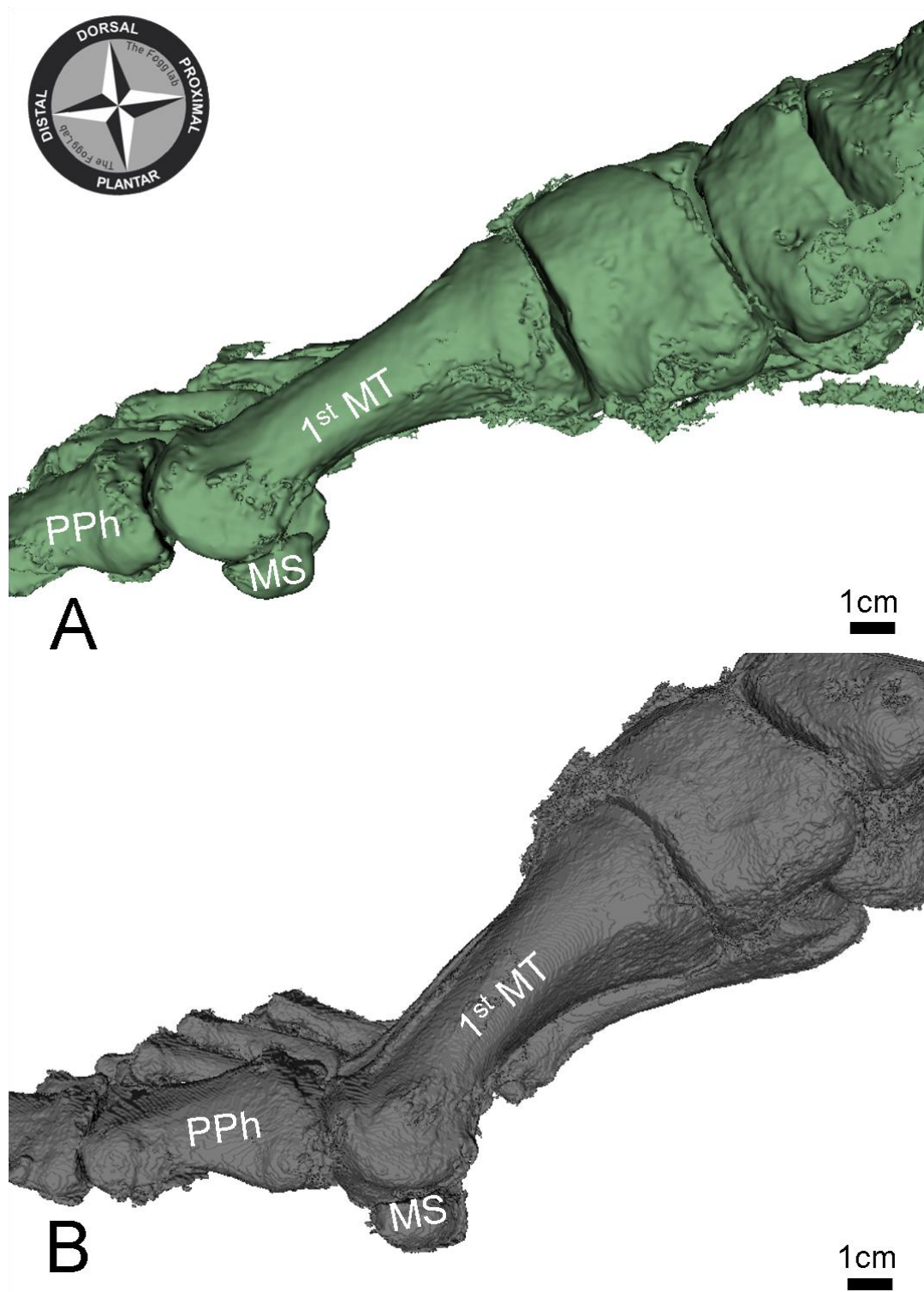


Figure 4.2.6. Medial views of weight bearing CT scans of a right foot, A - The control scan, barefoot with no heel height added. B - Barefoot with 5cm heel height.

MS: Medial sesamoid; PPh: Proximal phalanx; 1st MT: First metatarsal.

Figure continues on the next page.

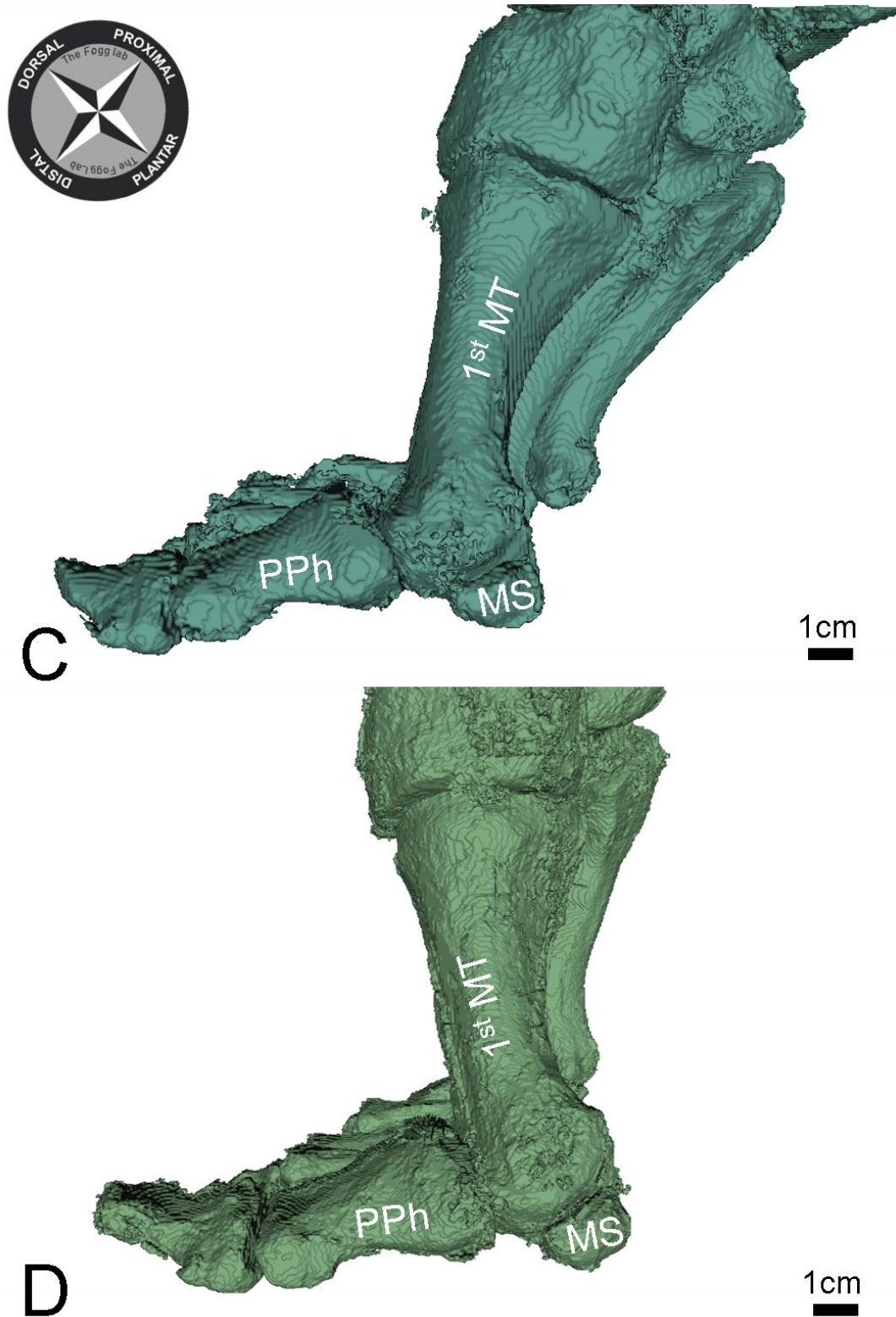


Figure 4.2.6. *continued*. Medial views of weight bearing CT scans of a right foot, C - Barefoot with a 10 cm heel height. D - Barefoot with a 13cm heel height essentially “demi-pointe”. MS: Medial sesamoid; PPh: Proximal phalanx; 1st MT: First metatarsal.

4.2.4 Discussion

Idiopathic avascular necrosis, sometimes called “Morbus Renander” (Kalweit *et al.*, 2003) or “Renander’s illness” (Toussirot *et al.*, 2003), is a condition first described in 1924 by Axel Renander (Renander, 1924) that affects young women more than any other demographic (Bartosiak *et al.*, 2019; Julsrud, 1997; Kalweit *et al.*, 2003; Toussirot *et al.*, 2003; Waizy *et al.*, 2008). In fact, it is described as an atypical presentation if it occurs in any other demographic (Williams *et al.*, 2009a), despite the first description being made on a 13 year old boy (Ogata *et al.*, 1986). This higher frequency of occurrence in young females and to a lesser extent, young boys has not been fully explained. The most popular explanation is microtrauma from running, jumping and dancing (Bartosiak *et al.*, 2019; Julsrud, 1997; Pinto *et al.*, 2010; Toussirot *et al.*, 2003). Habitual wearing of high heeled shoes is well known to adversely affect the forefoot (Broega *et al.*, 2017; Lewis *et al.*, 2017; Linder *et al.*, 1998; Prokop *et al.*, 2020). The position of the foot in a high heeled shoe is very similar to the “demi-pointe” position of a dancer, which is well known to put stress onto the HS and put them at risk of repetitive stress i.e., microtrauma (Prisk *et al.*, 2008). This undue pressure and stress on the HS or their blood supply could then lead to avascular necrosis, stress fractures and eventually osteoarthritis (Berkowitz *et al.*, 2019).

Previous studies focusing on the arterial supply to the HS used a variety of techniques, most notably dissection (Chamberland *et al.*, 1993;

Pretterklieber, 1990; Pretterklieber *et al.*, 1992; Shereff *et al.*, 1987), sometimes in conjunction with injection studies (Chamberland *et al.*, 1993; Shereff *et al.*, 1987; Sobel *et al.*, 1992) , as well as plastination, histology and diaphanisation techniques (Chamberland *et al.*, 1993; Rath *et al.*, 2009; Shereff *et al.*, 1987; Sobel *et al.*, 1992). The results of contrast-enhanced radiographs used in these studies have been deemed unclear and inaccurate (Pretterklieber *et al.*, 1992; Shereff *et al.*, 1987). Higher resolution CT and micro-CT were not used in the reviewed literature.

The nutrient artery for the medial sesamoid (MS) was supplied by the superficial branch of the medial plantar artery, or medial branch from the first metatarsal artery, the equivalent for the lateral sesamoid (LS) was supplied by the first plantar metatarsal artery and its lateral branch with variable contributions from the first dorsal metatarsal artery (Chamberland *et al.*, 1993; May Jr *et al.*, 1977; Pretterklieber, 1990; Pretterklieber *et al.*, 1992). Each sesamoid was reported to have 1-3 perforating branches, with most supplied by a single branch. It has also been suggested that HS blood supply was exclusively from branches of the medial plantar artery, with no contribution from the first plantar metatarsal artery (Chamberland *et al.*, 1993). It was also suggested that only one vessel consistently penetrated each HS, taking a proximal to distal course, leaving the distal poles of the HS less vascularised (Chamberland *et al.*, 1993). These findings are in contrast to studies carried out on similar populations in which the MS and LS had two to three nutrient arteries (Rath *et al.*, 2009; Sobel *et al.*, 1992). Of the nutrient arteries reaching a given HS, the most proximal nutrient artery tended to

have a longer intraosseous path and was the main supply to the HS, alongside a sometimes limited collateral supply (Chamberland *et al.*, 1993; Rath *et al.*, 2009; Sobel *et al.*, 1992). The HS blood supply may therefore be described as mostly anterograde, with minimal retrograde supply (Bartosiak *et al.*, 2019). These findings show a lack of significant collateral circulation to the HS, with a mostly proximally-based source. This may pre-dispose the HS to avascular necrosis and, non-union following a fracture, or disruption of the source artery during surgery or trauma.

The dominant blood supply of the HS coursed through the distal attachment of each flexor hallucis brevis tendon and from the midline of the plantar aspect of each HS. The inconsistent and small distal nutrient artery was reported to perforate the HS at their distal poles (Sobel *et al.*, 1992). The midline plantar nutrient artery is arguably the most at risk as it sits directly beneath the HS, which themselves are prone to large amounts of stress during normal gait. It has been theorised that disruption to this midline plantar nutrient artery before the ossification of the HS is a mechanism for bipartism (Jahss, 1981). Further to this, the MS has been reported to bear most of the weight within the HS complex, as it sits directly below the MT head; partism is most prevalent in the MS (Yammine, 2015). This theory relies on either the stresses of normal pre-ossification ambulation, sporting activities, or other more serious stress events to be sufficient to disrupting the blood supply to the plantar nutrient artery. The foot position of “demi-pointe”, which is mimicked in position by feet in high heeled shoes, causes a hyperextension of the hallux and tracks the HS distally (Crain *et al.*, 2016), focusing weight

upon the HS. Considering that the HS are subject to up to three times body weight during normal ambulation, this “demi-pointe” increases the pressure onto the HS substantially, perhaps enough to cause micro-traumatic events during most footsteps. This provides a theoretical pathomechanism for avascular necrosis of the HS, which warrants further investigation. At least, these findings support a suggestion of caution when releasing tissues near the HS, and particularly at their proximal poles.

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4.3.1 Summary

The hallucal sesamoid bones are essential features of the first ray of the foot. Optimal foot function relies on their accurate positioning and movement; they absorb and transmit large forces during basic activities, like walking. Deformation of the first ray, most commonly through disorders like hallux valgus (bunions), alters the position and mobility of the hallucal sesamoids. A range of clinical strategies, from conservative bracing to soft tissue release and first ray osteotomies, attempt to either restore their position or to remove their contribution to further deformation. The anatomical rationale for surgical release of these tissues, beyond the basic concept, does not appear to be based upon accurate anatomical information. The literature offered little consensus on a number of anatomical points. The series of studies presented in this thesis provide a clear and reproducible demonstration of the multitude of tissues which interact directly with the hallucal sesamoids. Some evidence was provided to support the likely mechanical nature of these interactions; both bones had the vast majority of their non-articular surfaces covered with soft tissue attachments, and these were demonstrated to be true entheses. Further studies are needed to confirm the specific enthesial nature of each attachment systematically, using healthy and pathological specimens and comparing the two would better help understand the aetiology of the disorders of the first ray but was beyond the scope of the study. The current data provide an overwhelming case for significant, distinct, multi-tissue attachments to each sesamoid.

The studies presented in this thesis confirmed some commonly observed attachments, such as the adductor hallucis tendons, but expanded understanding of these attachments. Detailed documentation of the soft tissue interdigitations through which these tendons, together with those of the flexor hallucis brevis muscle, formed a conjoined tendon were provided. The close and easily obscured relationship of this tendon to neighbouring tissues, also of likely mechanical importance, were documented and visualised, some of which for the first time. This thesis also presents the first known report of the superficial medial collateral ligament. Identification of such structures, and doing so consistently, may be testament to the careful development of techniques that minimise subjectivity and place an emphasis on reproducibility. Dissection can be extremely subjective, but the fascicular dissection strategy utilised, aimed to purposefully reduce such associated behaviour. Combining dissection with digital modelling not only provided unique means of visualising the findings, but also required a less subjective approach by focusing on specific fascicles of tissues, rather than their collective structures. It is hoped these approaches will be adopted by others to facilitate more meaningful comparison between studies.

There has been a change in the anatomical perspective of certain tendons and ligaments to be part of the periarticular tissues (Hoshika *et al.*, 2019; Nasu *et al.*, 2020; Tsutsumi *et al.*, 2020). The relation between capsular and extracapsular tissues has been poorly described. This may be due to most reviewed studies utilising methodologies that are highly subjective. The current series of studies utilised fascicular dissection,

allowing for the distinct determination of the course of individual fascicles.

This approach allows for the reproducible description of specific fascicular bundles, irrespective of their capsular relations. If adopted more broadly, this approach may lead to clearer and more consistent understanding of capsular relations around other joints.

The results presented in this thesis demonstrate a better, and more detailed, understanding of the anatomy of the hallucal sesamoid bones and their relations. These data will inform future studies and may also inform diagnosis and management of disorders of the first ray.

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Part 5

Appendices

Appendix 5.1

The Embalming Process of The University of Melbourne Body Donor Program

Equipment

- Porti Boy Pump: Variable pressure and flow. 220volts 50 cycles lamp. (Commercially available liquid pump).
- Cannulas and syringe fittings for Porti Boy tubing
- String
- Dissection instruments: Scalpel (size 20 blade on no. 4 scalpel handle, blunt curved Metzenbaum scissors, forceps, retractors and artery clamps)
- Syringe (if required) 20mL with 18 gauge needle
- Cordless drill with 5/32" bit
- Hair clippers
- Heat sealers (fixed and handheld available) and plastic for storage

Pre-embalming Preparation

1. Using hair clippers shave facial and scalp hair.
2. Transfer the body donor to a downdraft table and turn on the downdraft exhaust fan.
3. Make an incision distal to the mid inguinal ligament, overlying the femoral vessels. Expose the femoral artery (and vein – optional) using blunt dissection techniques. If the carotid artery is to be cannulated, expose via incision between the medial and lateral heads of sternocleidomastoid.
4. Cannulate the artery, both inferiorly and superiorly using a controlled valve and normal cannula respectively (alternatively, if only using one cannula, initially cannulate inferiorly and turn

superiorly for femoral or superiorly then inferiorly for carotid when required).

5. Ligate the vessel around each cannula to avoid leakages (A small incision also in the accompanying vein is optional, to aid embalming).
6. Make an incision in the scalp to expose the cranium. Drill hole (drill bit 4mm) in cranial vault entering superior sagittal sinus to relieve blood fluid pressure. Allow blood to drain.

Embalming

1. Pour Genelyn Arterial Anatomical fluid (Genelyn, Adelaide, Australia) into the canister of the Porti Boy variable pressure and flow pump (ESCO, Connecticut, USA) using a tap on the drum connected to the tubing through the lid of the Porti Boy. The lid must always remain on the canister of the Porti Boy to contain vapours produced by the embalming fluid.
2. Turn the switch on the bottom right hand corner of the pump to 'pulse' setting (note: this will not start the machine). To start machine, press black button in the centre of the pump and hold for a few seconds until pump starts.
3. Pressure can now be adjusted to between 15 and 25psi using the dial located on the front of the machine labelled 'Pressure'. This must be set with the rate of flow set to zero or with the flow valve closed.
4. Open the flow valve. Embalming fluid will now flow into the cannulated artery. Ensure pump maintains a pressure of between 15-25 psi throughout the embalming process.
5. Allow approx. 15 minutes for the lower limb to become firm (and if an incision in the vein was made, the outflow from the femoral vein becomes clear). If using a double cannula, close the inferior cannula and allow superior cannula to embalm the remainder of the body. Tie off the femoral artery (and vein –

optional) to trap embalming medium in the cadaver, allowing natural infusion.

Alternatively, if only using one cannula, remove cannula inferiorly and turn around and insert superiorly through the same incision in the artery. Tie off the artery inferior to the incision to contain embalming medium in the lower limb.

6. The rest of the body will require embalming to continue over 2-4 hours. The operator does not need to be present at all times but should check back regularly to assess the progression of embalming and refill the Porti Boy canister with embalming fluid as required.

When embalming is complete the skin of the cadaver will appear blotchy and all underlying flesh should be firm. - Appearance of the body donor should be bloated.

7. Following arterial embalming using the Porti-boy, the extremities of the cadaver may require manual injection to complete the embalming process. Lack of fluid reaching the extremities may be caused by limbs having an occluded artery or vein blocking perfusion through the vascular system. Where large regions of the cadaver do not embalm adequately (i.e., forearm), manual injection using the Porti-boy pump is necessary, equipped with a 38mm, 18 gauge needle.

1. Unclip/unscrew cannula from tubing and attach needle fitting.
2. Ensuring flow valve is closed, turn on machine.
3. Reduce pressure to approximately 10-15 psi.
4. Insert needle into area that requires manual injection and using the flow valve to control rate of flow, allow embalming fluid to flow into the tissues until they become firm. -Some regions may require injection into several compartments, i.e., flexor/extensor compartments of forearm.

5. For small regions i.e., fingers and toes, a 20ml syringe with 18 gauge needle should be used. -Using a syringe, inject up to 500ml (depending on cadaver) of the Genelyn Arterial Anatomical Fluid manually into the cranial vault to complete embalming.

Post-embalming

1. Remove cannulas and tie of ligature/string around vessels to avoid leakage.
2. The body donors are stored in sealed plastic bags
3. The cadaver can now be stored in the cool room at 5°C. It will be stored (where some leaching of perfusion solution occurs) until needed - this is not usually less than twelve weeks.
4. Clean and disinfect all surfaces and instruments, and flush Porti Boy pump

Appendix 5.2

Fascicular Dissection Protocol

Fascicular dissection is a strategic approach where the decision-making is made during the dissection process. It primarily relies upon blunt-sharp dissection (Table 5.7.1), i.e., using the edge of a scalpel blade to gently separate tissue, rather than actively cutting the tissue; this is not the same as blunt dissection, where less precise tension (e.g., from opening scissor arms) separates tissue along less precise planes.

1. Reach the structure(s) of interest by sharp and sharp-blunt dissection, retaining at least one layer of tissue superficial (typically fascia or fat) to the area of interest. When approaching the target area, progress should be checked under magnification (7-36x; M400 Photomakroskop, Wild Heerbrugg Ltd., Switzerland), and may be required to continue under magnification.
2. For tissues arranged in a regular, fascicular manner (ligament, tendon, muscle) identify the fascia immediately surrounding the structure of interest (i.e., epiligament, epitenon, epimysium) and carefully reflect this along the length of the structure. Where there is some evidence of structural margins observable, the fascia should be incised along the length of the target structure, approximately equidistant between the margins of the structure.
3. Make short, perpendicular incisions at either end of the first incision, bringing each close to the longitudinal margins of the target structure. This should be completed under magnification to ensure the margins are not encroached and deeper fascicles are not cut. Reflect the fascia to either side but do not excise it. This preserves potentially unseen relations at the structure margins.

4. With the deep fascia reflected, the fascicular orientation of the target structure should be more clearly visible. Using blunt-sharp dissection, carefully remove any internal fat or fascia, such that each fascicle can be traced along its entire length. Repeat this for as many fascicles as needed to meet the objectives of the study.
5. The same technical approach should be applied to non-fascicular tissues. These, however, lack a visual means of decision-making, so retention of these tissues remains more subjective and subject to the skill of the dissector.
6. The study objectives should include clear criteria for retention of tissues*. Once these criteria are met, excess tissue can be removed and the specimen documented (photographed, digitised with a laser scanner, digitised with a microscribe).

*In all of the individual studies in this thesis, an exploratory approach was maintained. For example, rather than retaining fascicles which connect one bone to another (as when trying to define a specific ligament), specific groups of fascicles were described based on common appearance/course. This included:

- fascicles which clearly attach to bone
- fascicles which interdigitate with other fascicular tissue
- fascicles which terminate in non-fascicular tissue

Table 5.7.1. Types of dissection

Type	Description
Blunt	Separation of tissue planes through the use of tension, typically in opposing directions, e.g., lifting a reflected layer away whilst compressing a retained layer. This allows quick exposure, but at the expense of control and does not maintain direct visualisation of the point of separation.
Sharp	Creation of a new division between tissues. Most simply put, sharp dissection requires cutting of the tissue (as with a scalpel blade or scissors). It allows direct visualisation of the first point of contact by the cutting edge, but this is lost as the edge is moved into the tissue.
Blunt-Sharp	Using the sharp edge of a scalpel blade angled such that it is almost parallel with the tissue of interest (to be retained), fine pressure can be applied under direct observation. In this process, the sharp edge never disappears from view (i.e., it does not cut), but is gently pressed against tissue made locally taut by retraction applied with forceps (on the tissue to be removed or mobilised). This allows the separation of tissues along natural planes ("blunt") but always under direct observation and more precise ("sharp").
Sharp-Blunt	Follows a similar philosophy to Blunt-Sharp but uses a scalpel blade or scissors to create a pathway along or between tissues. Local tension (on tissue to be removed or mobilised) is again applied by forceps. This tension is increased at the tissue junction of interest (e.g., fascia enveloping a blood vessel) by the application of a near parallel (to the tissue to be retained) scalpel blade, or closed scissors, which are opened in manner that only stretches the tissue to be removed (typically fascia) but does not "snap" the tissue. This approach maximises direct observation of tissue separation, as opposed to the traditional "blunt" approach.

Appendix 5.3

Microscribe Digitisation of Surfaces

These instructions apply to a MicroScribe G2X Digitiser (Immersion Corp., USA) used in conjunction with Rhinoceros 4.0 Software (Robert McNeel and Associates, USA).

These steps produce a 2D model of a surface in a 3D virtual space. These models allow for consideration of tissue area, curvature and relations in 3D, but are not volumetric.

All modelling was done in triplicate. Area measures for each lofted structure were used from each round of modelling to compare mean values for each round of modelling for each structure across the sample population. Where no significant difference ($p < 0.05$) was observed between rounds, modelling of that specific structure was deemed accurate and reproducible. Where significant differences ($p > 0.05$) were observed, those models were deemed inaccurate and removed from the study. If modelling of a specific structure was deemed inaccurate, the modelling process was refined (different stabilisation, different modelling sequence, etc.) for that specific structure until an accurate model could be produced. For the studies presented in this thesis, no structure models were deemed inaccurate through this approach.

5.8.1 *Getting started*

1. Turn on the computer
2. Plug the microscribe USB cable into the computer; the light on the back of microscribe should now be RED
3. Press the button on the back of the microscribe (directly behind the light); the light should turn GREEN
4. Open Rhinoceros 4.0
5. Select template file; this is normally "Small Objects-Millimeters"
6. Click the  logo; the program will now direct through calibrating the microscribe and your specimen; follow the instructions in the command dialogue box in the top left of the screen.
7. When prompted use the RIGHT pedal on the foot control to select each of the points indicated below:
8. Press ENTER to use the "World Origin" in Rhinoceros; you're now ready to start reconstructing!

5.8.2 *Reconstructing a surface*

1. Click the  logo.
2. The command dialogue box in the top left of the screen will indicate that you're ready for the "Start of Curve" and the microscribe cursor will become visible when you pass the tip close to the specimen
3. Use the RIGHT pedal on the foot control to select the first point of your curve; the command dialogue will change to "Next Point"
4. Continue selecting points along the specimen until your first curve is finished; Press ENTER to finish the curve
5. Press ENTER again to reload the curve tool. The command dialogue box will change to "Start Curve"
6. Repeat as per your first curve, but DO NOT let the lines cross!
Continue for additional curves until your surface is covered
7. From the menus at the top of the screen, select Surface → Loft
8. The command dialogue will prompt you to "Select Curves to Loft";
Start at one end of the series of curves and select (LEFT mouse button) one curve at a time; make sure to click close to the end of each curve, and ALWAYS at the same end of each successive curve;
Press ENTER when finished
9. The LOFT dialogue box will appear. Select TIGHT from the drop-down menu and press OK; you now have a reconstructed surface!

Appendix 5.4

Contrast-Enhanced Micro CT

1. To collect the sample to be micro CT scanned it must be cut to fit the chamber inside the micro CT scanner which is limited to about 5cm cubed. Draw an incision line on the body donor with a marker pen to ensure that the sample contains the region of interest. Mark a line 1.5cm proximal to the joint line of the hallux and a line 1cm distal to the joint line and a line running longitudinally along the mid dorsoplantar aspect of the hallux on both sides
2. Cut the tissues following the incision lines with a blade. Make sure the cut is deep such that the tip of the blade touches the bone, then use either a hacksaw with a fine blade attached (32TPI, 0.68mm kerf) or an oscillating bone saw. Once the distal and proximal cuts are made the cut separating the dorsal aspect of the hallux from the plantar aspect is completed
3. Dehydrate the sample in a series of 30%, 50%, and 70% ethanol solutions for at least 1 day each.
4. Place the sample in 70% ethanol until it is used for the staining.
5. Begin the phosphotungstic acid (PTA) staining process 1 week before micro-CT scanning is scheduled.
6. Prepare a 1% PTA solution in 70% ethanol, mix well with a magnetic stirrer.
7. Soak the specimens in the PTA solution on a magnetic stirrer for effective penetration. Leave the samples for 7–10 days (Fig X)
8. When the staining is completed, store the sample in 70% ethanol to prepare for scanning.
9. The stained samples can be maintained for several months, but it is recommended that the samples be scanned as soon as possible to ensure full staining.
10. Wrap the sample with clingfilm wrap tightly to prevent drying and keep the tissue firm.
11. Open the micro-CT scanner (SkyScan, Bruker, Kontich, Belgium) scanner and place the sample on the tray (Figure 2).
12. Set the scanning parameters as follows: source voltage (kV) = 100, source current (μA) = 100, Al + Cu filter, image pixel size (μm^2) = 26.91, pixels =

1936 × 1936, exposure (ms) = 700, rotation step (deg) = 0.6. The parameters may be modified according to the samples and/or scanners used.

13. The scanning can take between 2-4 hours depending on the intended resolution, specimen size and speed of the scanner.
14. Run the reconstruction software. Select Open Dataset on the Actions menu to launch the scanned files.
15. Select the Settings tab on the Reconstruction window. Set the parameters as follows: Ring artifacts reduction = 18, Beam-hardening correction (%) = 79.
16. Begin reconstruction by selecting Start on the Start tab. The final data will be stored in the designated folder.
4. Run the file resizing software. Select Source data set to launch the reconstructed files.
17. Select jpg on the Destination data set tab.
18. Choose the Resizing option 1/2 with a Quality option of No interpolation (fast).
19. Adjust the slide bar to 100 (highest) in the Image compression tab. Start converting.
20. NOTE: The resizing option is to avoid slowing down the computer speed when 3D rendered; however, it can result in lower resolution when resized extensively. We suggest resizing in half for acceptable resolution with better handling.
21. 3D reconstruction
22. Run the 3D volume rendering software.
23. Select Actions > Load volume data to launch the dataset.
24. Adjust the brightness and contrast level by modifying shape transfer function in histogram in the Transfer Function Editor tab.
4. Select Options > Lighting.
25. Select Shadows and Surface Lighting icons. These effects provide a realistic modelling tone.
26. Find the best view by moving (click and drag), rotating (right-click and drag), and zooming in or out of (scroll) the model.
7. Slide the plane (shift + click and drag in the inner direction) to show the sectional images (Figure 3).
27. Turn on Light icon. Adjust the lighting indication bar and find the best lighting for viewing. Then, turn off the icon and close the Lighting tab.
28. Select Options > Show > Clipping Box to hide the box for the final image.
29. Select Actions > Save image to store the image.

Appendix 5.5

Protocol for Dataset Segmentation

1. The data segmentation needs to be carried out on the smallest sized dataset possible to ensure that the software and hardware do not run too slowly and ensure smooth workflow
2. When the dataset is acquired, it will be in DICOM or TIFF formats
3. Downsize the dataset by uploading it into 3D Slicer (Pieper *et al.*, 2006) and cropping the dataset so as to include only the area to be segmented. If this is still too slow, especially when viewing in 3D, click the dropdown for “Show 3D” and uncheck “Surface Smoothing”
4. Import DICOM files and upload
5. Use “Modules” – “Converters” – “Crop Volume” – “Define cropping edges” and then “Apply crop”
6. Use “Modules”- “Segment Editor” – “Add” – “Name segment”
7. Use the segmenting tools, either thresholding, or grow from seeds, etc.
8. Once segments are made go to “Segmentation” – drop down – “Export to files”- “save as” .obj or .stl file types to be opened in Blender (Community BO, 2018).

References

- Pieper S, Lorensen B, Schroeder W, Kikinis R. (2006) The NA-MIC Kit: ITK, VTK, Pipelines, Grids and 3D Slicer as an Open Platform for the Medical Image Computing Community. *Proceedings of the 3rd IEEE International Symposium on Biomedical Imaging: From Nano to Macro*. **1**: 698-701.
- Community, B. O. (2018). Blender - a 3D modelling and rendering package. Stichting Blender Foundation, Amsterdam. Retrieved from <http://www.blender.org>

Appendix 5.6

Constructing a Three-Dimensional Model using the Artec Scanner

1. Prepare the specimen for scanning by ensuring that the structure of interest is clear and clean and dry, as reflective surfaces do not capture well with the scanner
2. If the specimen is too wet, blot dry after spraying with 70% ethanol, or if the surface is naturally reflective coat the surface with a chalk dust
3. Place the specimen to be scanned in middle of a clear space close to the workstation on either a turn table or suspended from a piece of string at an appropriate working height
4. The workstation area should have the laptop with Artec studio 15 (Artec 3D, Luxembourg) software on it, with a large bright screen facing the operator
5. Plug the Artec Space Spider scanner (Artec 3D, Luxembourg) into a power socket and the laptop and allow the device to warm up for 10 minutes
6. Place the Artec Space Spider at an operating distance from the specimen to be scanned (around 30cm) and press the trigger upwards to start scanning and observe on the screen if the scan is picking up the area of interest
7. Press the trigger up for a second time to start the recording of the scan, ensure that the area of interest is scanned continuously from differing angles and distances to ensure that every detail is captured
8. If the entire specimen is to be scanned, then slowly rotate the specimen whilst aiming the scanner at varying angles and distances to scan the entirety of the specimen
9. Once the recordings have been made enter the software and check for error within each scan
10. Check the error margin for each scan
 ” **Scan**” > **double click** “**Error**” > **click** “**Error**” until the highest value is at the top of the column > Select and remove any frame that has an error or 0.5 and above
11. “**Align**” - In the scan selection have one in blue and only one other in green
12. Then drag the specimens away from each other by pressing,
 “**Shift**” > **drag** so that they are beside each other in a similar position

13. Single click on the specimen at an area that is present on both specimens, do this for 3 different areas and then once all the fiducial points have been put in, then press
“Align markers” > “Align” > repeat for the new scan
14. Uncheck “Enable texture alignment” if you don’t want to wait too long
15. **“Apply” > “Tools” > “Registration” > “Fine Registration” > “Global registration” > “Fusion” > “Outlier removal” > “Sharp fusion” > “Postprocessing” > “Small-object filter” > “Hole filling”**
16. **“Texture” > “Select Spider Scan X”** that represents the best texture capture > **“Apply”**
17. Adjust the texture parameters to best fit then **“Apply”**
18. Now save the project and “Export” as .obj and texture to the same folder
19. The .obj file can then be opened with texture in Blender.

Appendix 5.7

Digital Graphics in Blender

These instructions relate the digital graphics software, Blender (Community BO, 2018).

Importing files

1. Import Stl or wavefront objects under File → Import
2. Adjust the cursor to the model/s
 - Choose 'Object' from the top of the screen when in Object Mode > "Set Origin" >
 - 'Origin to centre of mass' if only a single model, or
 - If a collection of models that are in separate layers but need to be moved together (to ensure that their spatial relationships are maintained), then move them as close to the central axis, and then set 'Origin to geometry'

Making the camera follow a path, while focusing on an object

1. Add NURBS curve or NURBS circle
 - 1.1. Edit shape by pressing TAB
 - 1.2. The curve can be divided or extruded, and positioning of different sections can be edited by selecting single/multiple dots
2. Add camera
 - 2.1. Make camera follow path of curve
 - 2.2. Click on camera and readjust
 - Move to rough location and angle as to how you want it positioned and the viewpoint to be oriented

- Select both camera and path, and make the camera follow the path by either:

a. Click Ctrl + P > Follow path

- Snap camera to centre of selected item > Select edit mode of path (TAB), and select point where you want the camera to start its path
- Shift + S and select Cursor to selected
- Exit edit mode (TAB again)
- Select camera and move it to cursor; shift + S > Selection to cursor

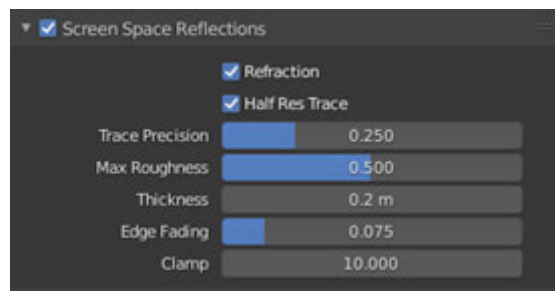
Note: If the camera is positioned at the wrong end of the NURBS curve at 0 on the 'Timeline', then you can right click on the curve and choose Mirror and select which plane you would like to mirror it in

b. Add object constraint for camera

- Follow path > Target: NurbsPath (or curve for whatever curve you want the camera to follow)
- Click animate path
- Make camera focus on a target regardless of where it is moving
 - a. Add an Empty (doesn't show up in final animation)
 - b. Select both camera and empty
 - Clt+T > tract to constraint option
 - OR just select camera and add a constraint in the side properties menu

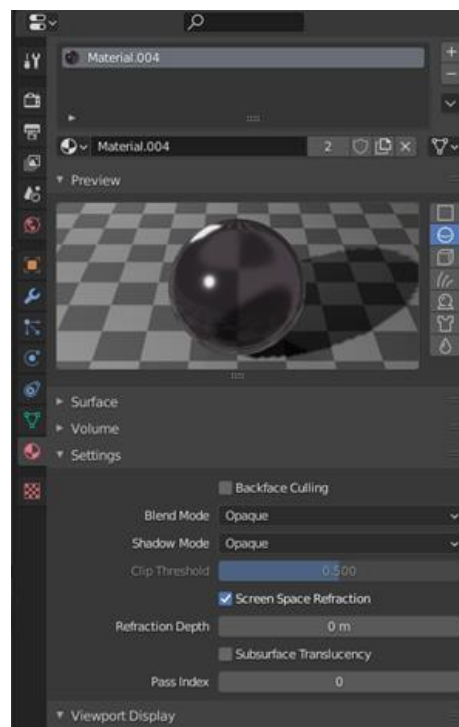
Make an object transparent

1. Under the Properties tab, open 'Render Properties'



Note: Is only available for Eevee Render Engine

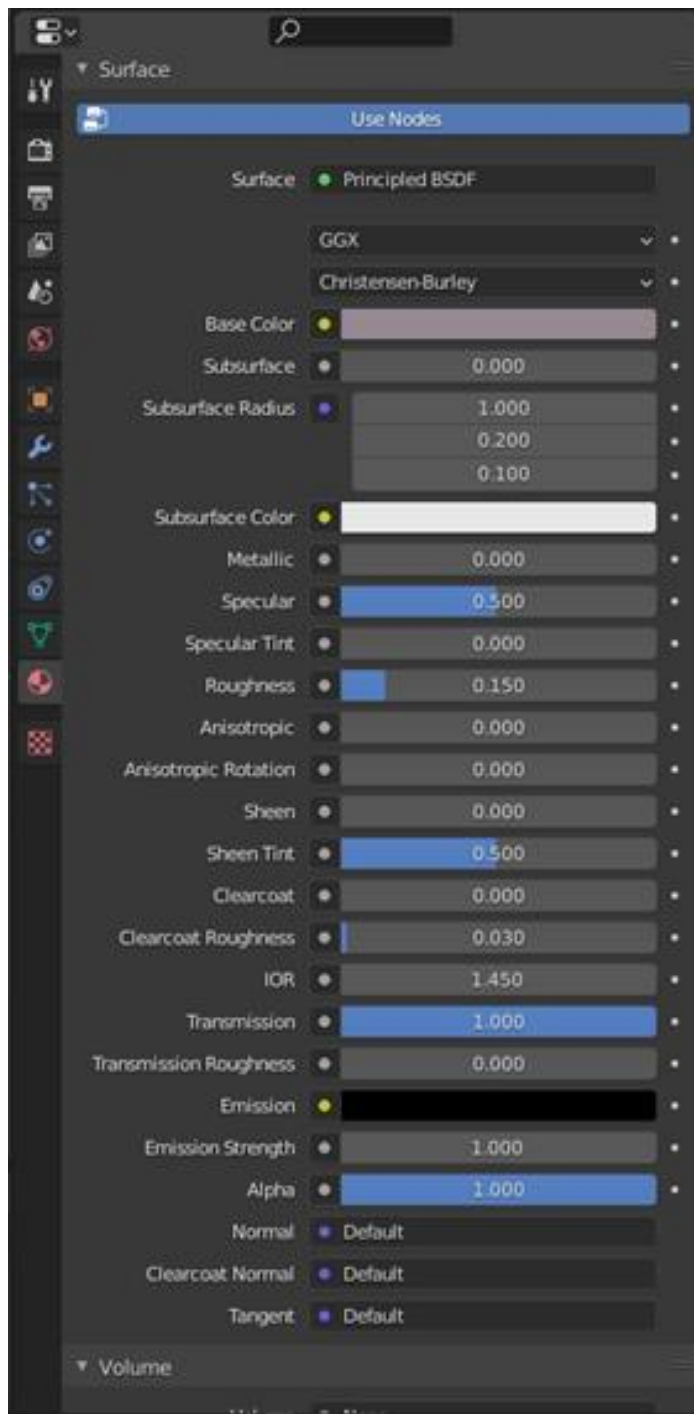
2. Tick 'Screen Space Reflections'
3. Select object that you want to make transparent



4. Choose '**Material Properties**' under the Properties tab, and scroll down to '**Settings**', and tick '**Screen Space Refraction**'
5. Still under 'Material Properties', expand the 'Surface' settings

'Transmission' = 1.000, and 'Roughness' <0.500 (note: a roughness of 0.000 will make the surface matte, whilst having it >0.000<0.500 will make the surface appear glossy)

6. You can also adjust the colour of the object under 'Base Color' under the 'Surface' settings



Taking photos and videos in Blender

1. Adjust camera to the desired location (ensuring that on the timeline, its position is set to 0 for the initial desired position if following a path for a movie)
2. Under the Properties menu, select the 'Output properties' tab, and expand the 'Output' tab
 - Choose the file you wish to save the image/video under
 - Select the desired File Format, e.g., PNG or JPEG for images, and AVI JPEG for videos
 - Adjust quality to desired level (100% if you can)
 - For videos, you can adjust the length of the video and the frames per second above, under the 'Dimensions' tab
 - You can also adjust the Start and End in the Timeline
2. In the top left-hand corner, under the Ribbon, choose the 'Render' drop down menu and select 'Render Image' or 'Render Animation'
 - *Note:* to get better quality images and videos, change the 'Render Engine' under the 'Render Properties' tab, to Cycles (otherwise have it as Eevee) first
3. You may need to 'Save as' once the image/animation has been processed if it has not automatically saved in the previously selected folder

References

Community, B. O. (2018). Blender - a 3D modelling and rendering package. Stichting Blender Foundation, Amsterdam. Retrieved from <http://www.blender.org>

Appendix 5.8

Adding Texture in Blender

1. If using an Artec scan export the model as an .obj file, and in Blender go to “File” – “import” – “Wavefront (.obj)” – Find the file – “Import OBJ”
2. Click on the model and right click – “Set Origin” – “Geometry to Origin”
3. This should centralise the model, click the “Viewport Shading” globe in the upper right corner to see if the texture is added
4. The model may look shiny and is still very big, scale it down if it is too large – “Scale” left column
5. To reduce the glossy appearance, go to the “Shading” tab – in the node screen find “Principled BSDF” – “Specular” turn down to 0.00

Appendix 5.9

Painting Digital Model Surfaces in Blender

1. Ensure the surface/object to be painted has a texture already, and has been UV unwrapped
2. To UV unwrap an object, select the object and go to the UV editing tab, at the top of the right screen select "UV" then select "Unwrap" or "Smart UV project".
3. In "Layout" select the surface/object to be painted
4. Hit tab to transition into edit mode
5. The selected object should appear as a mesh, on the top of the screen select the "mesh", go to "normals" then select "flip", a small text should appear on the bottom left hand side of the window reading "normals flipped"
6. Select the "texture paint" tab, in the right window use the brush to paint onto the surface of the object, the radius and colour of the brush can be changes at the top of the screen.

Appendix 5.10

Protocol for In-Lab X-Ray Imaging

1. Plain radiographs are carried out when examining specimens before dissection to establish if they have any deformity relevant to the hallux, such as hallux valgus. Also check for surgical hardware, check for partite sesamoids and use to confirm vascular perfusion of contrast).
2. The specimens are radiographed using a Progeny Linear MC150 collimator with Fujifilm FCR CapsulaX digital X-ray acquisition.
3. Turn on the Fujifilm FCR XL2 acquisition device and associated computer, name the study in the Fujifilm CR software.
4. Turn on the X-ray arm and ionizing source from inside of the control booth, set the voltage and current. Because specimen radiation exposure is not a major consideration low tube voltage (50 kVp, kilovoltage peak), high tube current (500 mAs, milliamperes) can be used to prevent X-ray scatter. Quick testing scans use a lower exposure at a tube voltage of 55Kv and low tube current of 4mAs.
5. Place the specimen in position on top of the X-ray plate with Styrofoam wedges for accurate radiolucent and stable positioning.
6. A dorso-plantar plain radiograph is taken of the entire foot (AP Foot), with the plantar aspect of the foot firmly on the X-Ray plate and the ionising source 30cm away directly above.
7. Additional subsequent medial to lateral and lateral to medial scans are made in plane with the ionising source. Medial oblique and Navicular views and close views are also used when a closer examination of certain structures is required.
8. Retrieve the X-ray plate and feed it into the Fujifilm FCR acquisition device, and wait for the digitisation of the X-ray onto the software
9. Examine the scan by pressing "QA" and adjusting contrast and brightness by right clicking and dragging across the image, then press "DICOM" to save the DICOM file to a named folder.

Appendix 5.11

Protocol for Computed Tomography Imaging

The Computed tomography imaging technique was carried out at The Melbourne Brain Centre Imaging Unit on a Siemens Biograph 128-slice ultraHD-PET CT scanner.

1. Obtain the desired number of feet to be scanned, all amputated from ~2cm proximal to malleoli and imaged whole, usually following microvascular injection.
2. Arrange feet within a long expanded polystyrene box, chosen for its low-density. The limbs were fixed in place using small blocks of expanded polystyrene to prevent artefact from movement of the specimen as the CT gantry advanced as well as to ensure that the specimens do not touch one another. Layer the feet onto one another using sheets of expanded polystyrene as (Figure A5.11.1).
3. Set the scanning parameters (Table A5.11.1). These should be adjusted according to specimen, contrast or user differences. Image each specimen three times at 80 kV and 700 mAs and then at 140 kV and 500 mAs. Each set of three images should then be averaged, giving an image similar to that which would be obtained at 2100 and 1500 mAs respectively, providing higher detail and resolution than would be obtainable in a single scan without overheating the scanner
4. Make a reconstruction at a diameter of 50mm, distance source to detector 1085.6mm, distance source to patient: 595mm.
5. It is notable that this correlates to an extremely high dose of radiation, significantly higher than that used in clinical CT.
6. Perform subsequent reconstructions with SAFIRE (Siemens, Germany) with 0.3/0.6mm slices.

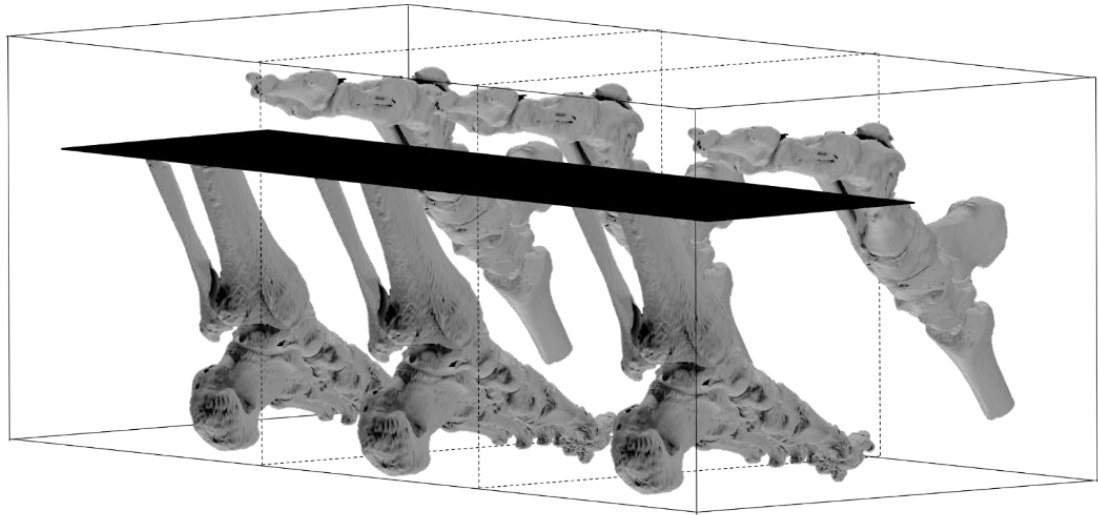


Figure A5.11.1. Feet are piled into a polystyrene box. They are lined up next to each other and on top of each other, separated by additional polystyrene (black rectangle) to ensure that they are not touching each other. This enables multiple feet to be included in a single scan.

Table A5.11.1. Siemens Biograph 128-Slice ultraHD-PET CT Scanner Settings

Machine	SIEMENS CT/PET Biograph 128 Scanner
Voltage (kVP)	120
Source current (μA)	385
Filter type	FLAT
Pixel spacing (mm)	0.77
Pixel resolution (mm)	376 x 376
Table feed per rotation (mm)	13.4 (clockwise)
Exposure (mSv)	1100

Appendix 5.12

Protocol for Band Sawing Specimens

1. Place the blade centrally on the Barnes Blademaster MK1 Bandsaw (HT Barnes, Sydney, Australia), wheels (4tpi, 0.55mm kerf)
2. Adjust blade guard to the size of the specimen to be cut to ensure there is a minimum of exposed blade whilst cutting.
3. Switch on exhaust fan to draw away any fumes/bone dust created whilst cutting specimen. The switch for activation of the exhaust fan is located on the west wall of the room. It is labelled 'embalming room exhaust fan on/off'. A green light on the switch will illuminate to indicate that the fan is operating. A Nederman Arm can also be used to draw away fumes
4. Position specimen on the sliding tray of the bandsaw. Ensure that the specimen is stable before commencing the cut and that the tray is clean and free of obstructions.
5. Turn on the bandsaw.
6. Whenever possible, use the guide installed on the bandsaw to assist in moving the specimen past the blade.
7. Guide specimen towards the blade keeping a relaxed but firm grip on the tissue.
8. For single sectioned specimens, collect and wash down specimen along cut surface, and analyse/dissect according to the fascicular dissection approach (see Appendix 5.7)
9. For 2-3mm thick specimen sections, retrieve them from tray with a flat bladed tool, such as a broad knife or a thin spatula to keep the tissue section from being deformed
10. Place the specimen section onto a drainage tray and wash off any sawing debris from the cut surfaces with cool water
11. Place the specimen section onto a specimen tray with appropriate labelling and keep cool
12. Before passing the specimen through the bandsaw again, use a paint brush to brush liquid nitrogen onto the cut surface to keep the tissue firm whilst being cut.

13. Once all specimen sections are gathered photograph each side of section, place each section onto a light table OR place on a black sheet under a high-definition digital camera (EOS 5D Mark III, Canon, Japan)
14. Upload and organise the photographs so as to align and view the images in a sequential manner through the specimen in order to follow the structures of interest.

Appendix 5.13

Protocol for Decalcified Specimen Sectional Imaging

1. Prepare the specimen for decalcification, ensure the specimen needs to be decalcified, i.e., is in part made up of calcified tissue, otherwise move to step 13.
2. Reduce the specimen size to represent only the structures of interest to reduce processing time, if the bone surface is cut it will shorten the processing time.
3. Immerse the block (of approximate volume x) into approximately 4x volume of a solution of 1% EDTA and 9.5% nitric acid.
4. Place the container on a magnetic stirrer, add a large stirring flea and cover the container (sealing film or cling film). Ensure stirring is just forceful enough to gently move the block,
5. Leave overnight.
6. Check the next morning, the fluid should now be yellow. Change the fluid and stir for 4 hours.
7. After 4 hours the fluid should again be yellow. Change the fluid again.
8. Wait another 4 hours and change the fluid once more. Leave it stirring overnight.
9. Check the next morning. Remove the specimen and gently compress it with a blunt, flat probe (or the base of a pair of forceps); it should feel slightly soft on all surfaces. If this is not the case, repeat steps 5-8, doing a compression test at each change. Stop the process once it feels soft.
10. Place the specimen in a 4x volume solution of 12% EDTA. Leave to stir overnight.
11. Check the next morning. The fluid may be slightly yellow. If this is the case, change the fluid and leave to stir. Do this daily until the fluid no longer discolours.
12. The final decalcification with EDTA may take up to two weeks with daily changes (fine to leave over a weekend though).
13. Check for full decalcification with the use of X-ray (see Appendix 5.10).

14. The next stage requires the specimen to be embedded. Various methods were trialled during the candidature.

Gelatin embedding

- a. Warm the specimen to 60C to help the gelatin embedding
- b. Suspend the warmed specimen in a mould appropriately sized into which pour a 20-30% gelatin hot water mix. Alternative: While setting the gelatin, keep the specimen in a vacuum oven at 200mmHg at 60C for two hours.
- c. Let the gelatin set for two hours in the cold room

Paraffin embedding

- a. See Histology protocol in appendix X, including vacuum oven stage.

Polyurethane embedding

- a. Suspend the specimen in an appropriately sized mould into which pour an equal mix of part A and Part B expanding rigid polyurethane foam (Dalchem, Australia).
- b. Wait a full day for it cure before breaking the mould apart and trim before sectioning.

Sectioning

- a. Cut specimen into 1-10mm sections sliding the pusher gently across the blade collecting the section with a flat and smooth board, such as Perspex ensuring no bending of the section

Section Imaging

- a. Lay sections on a light table to be photographed with a high definition camera (Canon EOS 5D with either a Canon Macro 100mm lens, or a Canon 35mm lens)

- b. Photograph both sides ensuring the image capture is done in a serial manner
- c. Upload the photographs and align all the images in image j specimen edges to appreciate their serial nature.
- d. The sections can be used as is or can be further processed with macro staining to highlight tissue contrasts

Appendix 5.14

Protocol for Large Specimen Histology

1. To collect the sample to be processed for histology it must be cut to fit the histology cassette (5cm X 4cm) Do this by drawing an incision line on the body donor with a marker pen to ensure that the sample contains the region of interest. Marking a line 1.5cm proximal to the joint line of the hallux and a line 1cm distal to the joint line and a line running longitudinally along the mid dorsoplantar aspect of the hallux on both sides, then mark a line on the plantar aspect of the hallux along the tendon of the flexor hallucis longus (FHL)tendon
2. Cut the tissues following the incision lines with a number 10 scalpel blade make sure the cut is deep such that the tip of the blade touches the bone, then use either a hacksaw with a fine blade attached (32TPI, 0.68mm kerf) or an oscillating bone saw. Once the distal and proximal coronal cuts are made, complete the axial longitudinal cut separating the dorsal aspect of the hallux from the plantar aspect. With the scalpel follow the midline of the hallux to reveal and reflect the FHL once the roof of the FHL tunnel is found between the two hallucal sesamoids, cut through midline of the intersesamoid ligament onto the MT and complete the cut with the hacksaw or oscillating saw
3. Prepare the specimen for decalcification by immersing the block (of approximate volume x) into approximately 4x volume of a solution of 1% EDTA and 9.5% nitric acid.
4. Place the container on a magnetic stirrer, add a large stirring flea and cover the container (sealing film or cling film). Ensure stirring is just forceful enough to gently move the block,
5. Leave overnight.
6. Check the next morning, the fluid should now be yellow. Change the fluid and stir for 4 hours.
7. After 4 hours the fluid should again be yellow. Change the fluid again.

8. Wait another 4 hours and change the fluid once more. Leave it stirring overnight.
9. Check the next morning. Remove the specimen and gently compress it with a blunt, flat probe (or the base of a pair of forceps); it should feel slightly soft on all surfaces. If this is not the case, repeat steps 5-8, doing a compression test at each change. Stop the process once it feels soft.
10. Place the specimen in a 4x volume solution of 12% EDTA. Leave to stir overnight.
11. Check the next morning. The fluid may be slightly yellow. If this is the case, change the fluid and leave to stir. Do this daily until the fluid no longer discolours.
12. The final decalcification with EDTA may take up to two weeks with daily changes (fine to leave over a weekend though).
13. The specimen is now ready for embedding, which can be done a number of ways. The two methods used for this research are presented below.

The Double Embedding Method

1. Place the specimen in 50% ethanol all day (minimum of 5 hours)
2. 70% ethanol overnight
3. 95% ethanol all day (minimum. 5 hours)
4. Absolute ethanol 1.5 hours
5. Absolute ethanol (new change) overnight
6. 50:50 absolute ethanol: diethyl ether half day (in fume hood)
7. 50:50 absolute ethanol: diethyl ether PLUS 1% cellulose nitrate half day (in fume hood)
8. 50:50 absolute ethanol: diethyl ether PLUS 1% cellulose nitrate overnight (in fume hood)
9. 50:50 absolute ethanol: diethyl ether PLUS 1% cellulose nitrate half day (in fume hood)
10. Clear in amyl acetate for 30 minutes (in fume hood)
11. Dry on paper (in fume hood) for at least 1 hour
12. Immerse in liquid paraffin wax (1st wax), 60 minutes (in oven)

13. Immerse in 2nd wax (new wax), 30 minutes (in oven)
14. Immerse in 3rd wax (new wax) @800 mbar, 30 minutes (in vacuum oven)
15. DO NOT open the oven: increase vacuum pressure to 500mbar, 30 minutes (in vacuum oven)
16. GENTLY and SLOWLY release the vacuum and open the oven
17. Immerse in 4th wax (new wax) @500 mbar, 1-2 hours (in vacuum oven)
18. Place tissue block in mould and fill with liquid wax. Allow to cool on cold plate. Once the surface is firm place in a fridge until ready to cut. The mould in which the block will be placed needs to have enough wax around the block to support it through the longer cutting cycle necessitated by the size of the block, ensuring that there is at least 0.5cm of wax between the specimen and the edge of the block.

The Single Embedding Method

1. Rinse the specimen of the decalcification solution in a large volume of fresh water for 1 day
2. Fix the specimen in a 10% formalin solution
3. Place the specimen in 50% ethanol all day (minimum of 5 hours)
4. 70% ethanol overnight
5. 95% ethanol all day (minimum. 5 hours)
6. Absolute ethanol 1.5 hours
7. Absolute ethanol (new change) overnight
8. Xylene for 16 hours
9. Then into the embedding machine in the histology cassette for a number of xylene and wax baths

Sectioning with Rotary Microtome

1. Secure the histology cassette and block tightly on the microtome, with the block face trimmed by a number of quick cycles
2. Capture the section in the water bath and float the section onto the slide
3. Leave slice in oven to cure overnight

Staining Procedure

To provide the best contrast between tissues of different densities, this modification of the classic Masson's Trichrome technique is recommended. It was particularly optimised for contrasting the dense organisation of ligaments with the comparatively loose arrangement of non-ligamentous capsular tissue (Fogg, 2004).

Ingredients

- Ponceau de xylydine phosphomolybdic acid.
- Acid fuchsin.
- Glacial acetic acid.
- Light green SF.
- Wiegert's A and B1 USE MAYER'S IF AVAILABLE
- Hydrochloric acid.
- Mixed solutions of Wiegert's A and B will only last for 2 days

Stains

1. Cytoplasmic Red

- A = 1% ponceau de xylydine in 1% acetic acid
- B = 1% acid fuchsin in 1% acetic acid
- Mix together in a ration of 2A: 1B
- To make 300mL:
 - A = 2g ponceau de xylydine + 2mL acetic acid in 200ml H₂O
 - B = 1g acid fuchsin + 1mL acetic acid in 100mL H₂O
- The final pH $\approx$ 3.05

2. Light Green

- 2g Light Green SF + 2mL acetic acid + 100mL H₂O
- Final pH $\approx$ 2.85

Procedure

1. Dewax in HistoClear for 10-15 minutes.
2. Hydration: Bring sections to water using the following sequence:
3. Absolute Alcohol 2 minutes.
4. Absolute Alcohol 2 minutes.
5. 90% Alcohol 2 minutes.
6. 70% Alcohol 4 minutes.
7. Rinse in running water 4 minutes.
8. Stain in Mayer's Haematoxylin 8 minutes.
9. Blue in running tap water for approx. 10 minutes.
10. Check that only nuclei are stained
11. Stain in Cytoplasmic Red for 1 minute.
12. Rinse in two washes (dips) of 1% acetic acid.
13. Displace in 4% phosphomolybdic acid for 2 minutes.
14. Rinse in 1 wash of 1% acetic acid.
15. Stain with Light Green for 35-70 seconds (may have to vary time).
16. Rinse in 1 wash of 1% acetic acid.

Dehydration

Blot, and then dehydrate using the following sequence:

1. 70% Alcohol 1 minute.
2. 90% Alcohol 1 minute.
3. Absolute Alcohol 2 minutes.
4. Absolute Alcohol 3 minutes.
5. Clear in HistoClear 10-15 minutes.
6. Second HistoClear 5 minutes.
7. Mount slides in DPX (mounting medium), in fume hood.

Appendix 5.15

Protocol for Weight-Bearing CT Scanning

Weightbearing CT scanning was carried out at Victoria House Imaging Centre, part of the I-MED Radiology Network, using a PlanMed Verity Weight Bearing CT scanner.

1. For the weight bearing CT scan, the patient must be able to stand on one leg with support for at least 10 minutes.
2. Place the patient foot into the CT field of view in the position required for the study, with or without footwear with and without polystyrene blocking to simulate heel lift.
3. Start the scan with the desired parameters (Table A5.15.1).

Include the variables into the study as separate scans, the variables are:

- Footwear such as barefoot or 56mm biomechanical footbed wide toe box (96mm-63mm taper) heels (Corella, Bared, Australia). Increase heel height with both types of footwear with polystyrene blocks cut to 5cm, 10cm and 13cm sizes.
- 1- The built in reconstruction software within the PlanMed verity scanner prepares the DICOM stack to then be analysed as laid out in other protocols.

Table A5.15.1. Settings for the PlanMed Verity Weight-Bearing CT Scanner

Machine	PlanMed Verity CT
Voltage (kVP)	96
Source current (μA)	385
Filter type	FLAT
Pixel spacing (mm)	0.25\0.25
Pixel resolution (mm)	376 x 376

Appendix 5.16

Protocol for Micro-Vascular Injection of Contrast Material

1. Harvest the foot by making an axial cut through the leg 2cm proximal to the medial malleolus.
2. Cannulate the posterior tibial artery with a 6Fr open-ended ureteral catheter (Cook Medical) trying to insert it as far distally into the artery as possible. Cannulate the anterior tibial artery and fibular artery if possible, depending on artery size and clotting.
3. Place the specimen in a bath of warm water (40-50C) for at least 40 minutes while preparing for injection.
4. Using the cannula, circulate a warm mixture of enzymatic cleaner such as (Biozet Attack, Kao, Japan) through the foot for 30 minutes with the use of the peristaltic pump (Cole-Parmer Masterflex® Peristaltic pump 7553)
5. Flush the specimen with warm water for 10 minutes.
6. Make up the contrast solution with warm water, 10% gelatine, 15% Barium Sulphate and optional dye (red, blue, black).
7. Start injection of contrast solution at a rate between 0.5-1.5mL/second whilst keeping all elements contained in the contrast solution warm.
8. Control any leaking at the proximal cut during perfusion with the help of haemostats to ensure maximal pressures within the specimen.
9. Once the nail bed of the hallux is discoloured to the colour of the dye used then the perfusion is finished, keep perfusing for another 2-3 minutes.
10. Take the specimen to the cool room to set the gelatine contrast solution.
11. Perfusion is confirmed via X-Ray imaging (Figure A5.16.1).

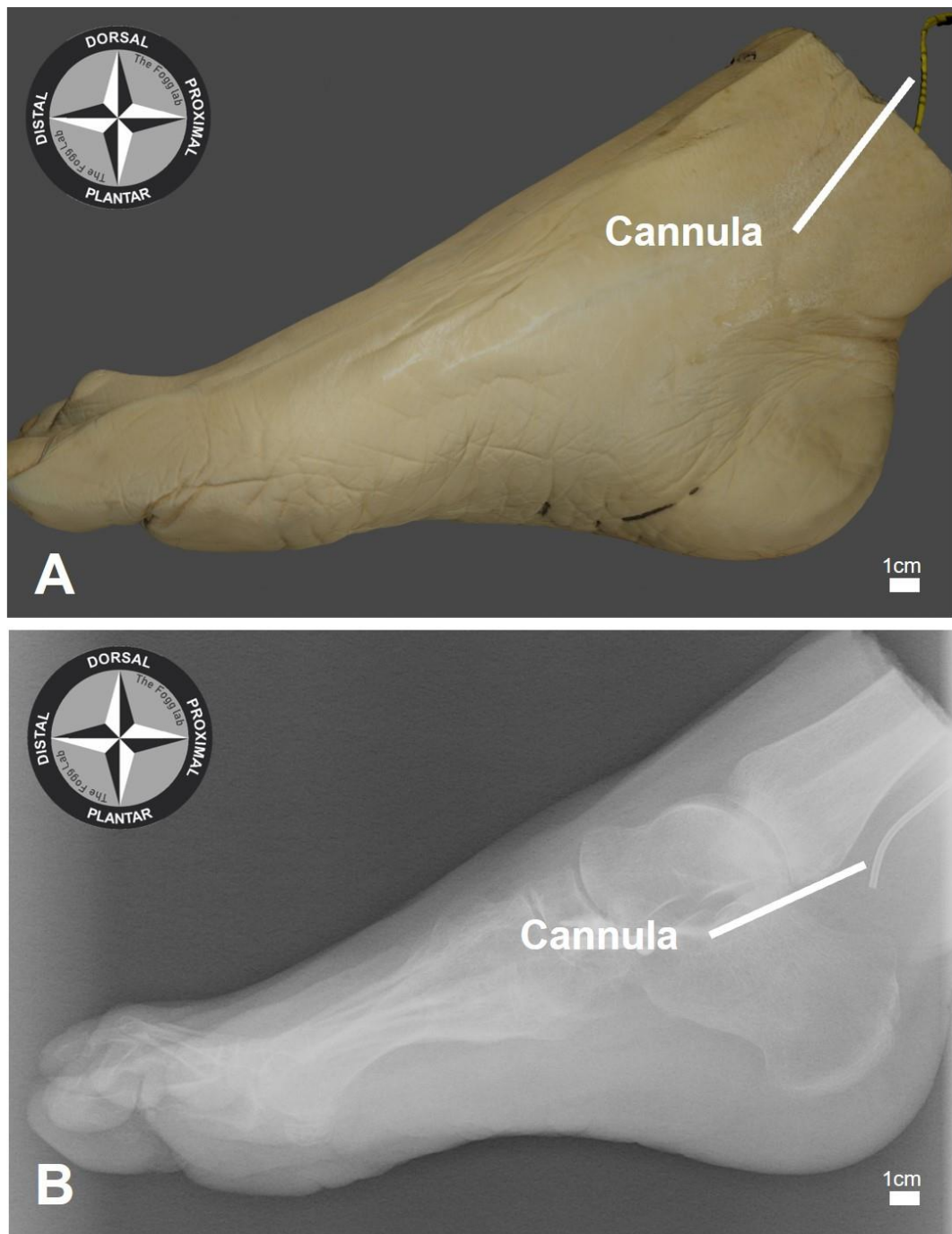


Figure A5.16.1. A- Medial view of a reconstructed model of a 3D texture scan of a left foot, the posterior tibial artery is cannulated with a catheter. B - Medial to lateral plain radiograph of the same foot to confirm cannulation and visualise the bony anatomy. *Figure continues on next page.*

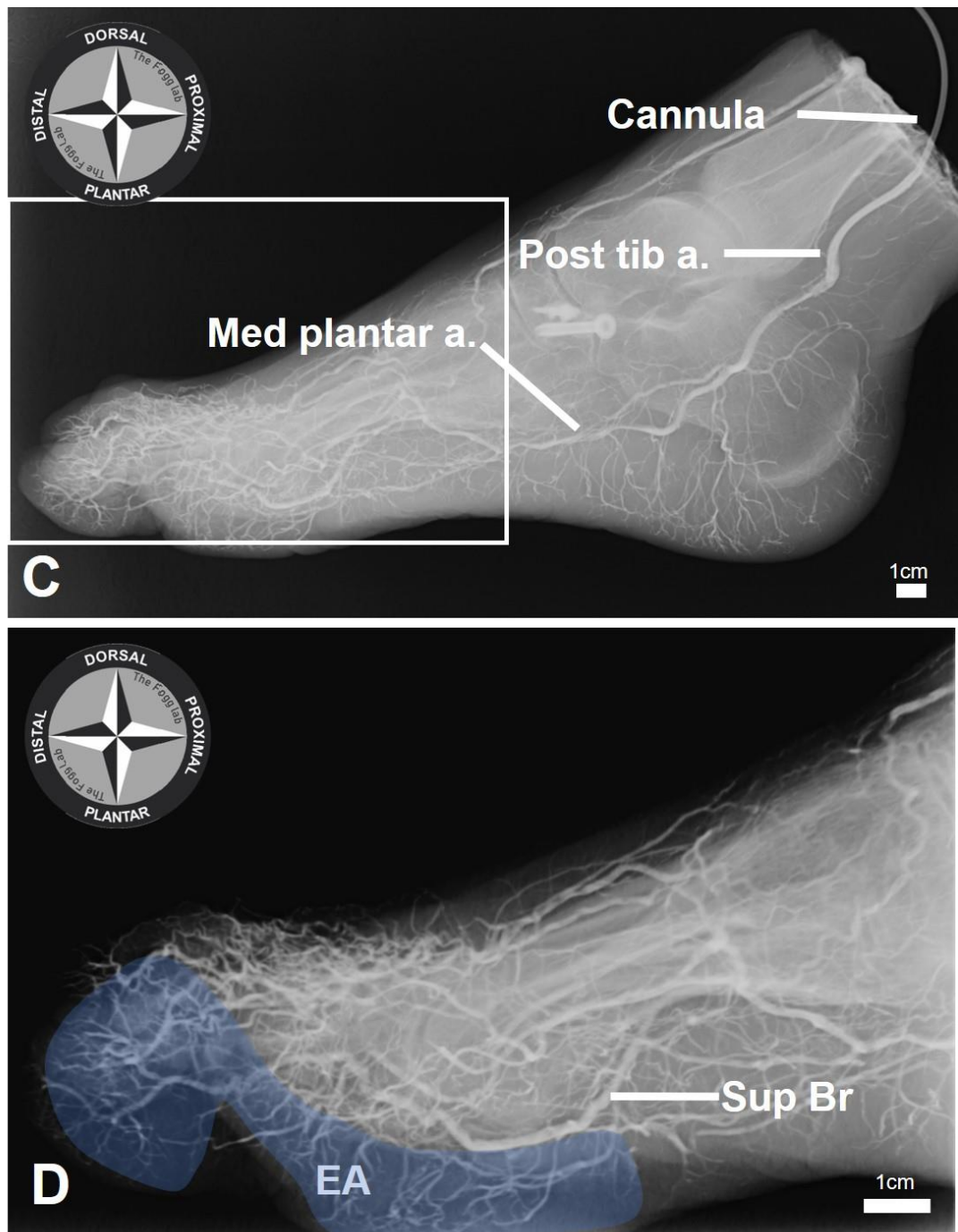


Figure A5.16.1 **continued**. C – Medial to lateral plain radiograph of the same foot after microsurgical injection of contrast material, confirming adequate perfusion. D – Medial to lateral plain radiograph of the distal foot to confirm perfusion of distal nutrient and anastomotic arteries. Post tib a.: Posterior tibial artery, Med plantar a.: Medial plantar artery, Sup Br: Superficial branch of the medial plantar artery, EA: Anastomotic network of the pulp of the hallux.