QUALITATIVE AND QUANTITATIVE MORPHOLOGICAL STUDY OF FLEXOR HALLUCIS LONGUS IMPLICATED IN TENDON HARVESTING AND TRANSFER

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A Dissertation Submitted in Partial Fulfillment of the Requirements
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การศึกษาทางสัณฐานวิทยาเชิงคุณภาพและเชิงปริมาณของ flexor hallucis longus ที่เกี่ยวเนื่องกับการเก็บและการผ่าตัดปลูกย้ายเอ็นกล้ามเนื้อ

น.ส.เปริน วันแอเลาะ

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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Thesis Title	QUALITATIVE AND QUANTITATIVE MORPHOLOGICAL STUDY OF FLEXOR HALLUCIS LONGUS IMPLICATED IN TENDON HARVESTING AND TRANSFER
By	Miss Perin Wan-ae-loh
Field of Study	Medical Sciences
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เปริน วันแอเลาะ : การศึกษาทางสัณฐานวิทยาเชิงคุณภาพและเชิงปริมาณของ flexor hallucis longus ที่เกี่ยวเนื่องกับการเก็บและการผ่าตัดปลูกย้ายเอ็นกล้ามเนื้อ. (QUALITATIVE AND QUANTITATIVE MORPHOLOGICAL STUDY OF FLEXOR HALLUCIS LONGUS IMPLICATED IN TENDON HARVESTING AND TRANSFER) อ.ที่ปรึกษาหลัก : ศ. พญ.วิไล ชินธเนศ

การผ่าตัดปลูกย้ายเอ็นกล้ามเนื้อ Flexor halluces longus (FHL) เป็นวิธีที่ใช้ในการรักษา Achilles tendinopathies อย่างแพร่หลาย แต่ยังพบรายงานการเกิดภาวะแทรกซ้อน เช่น การบาดเจ็บของหลอดเลือดและเส้นประสาท และการสูญเสียหน้าที่ของนิ้วเท้าหลังการผ่าตัด การศึกษาครั้งนี้จึงมีวัตถุประสงค์เพื่อศึกษาลักษณะทางสัณฐานวิทยาและตำแหน่งของรอยต่อระหว่างกล้ามเนื้อและเอ็นกล้ามเนื้อ FHL (MTJ) การกำหนดตำแหน่งและตำแหน่งบนผิวของ Master knot of Henry (MKH) โดยเทียบกับจุดอ้างอิง คือ ตาตุ่มด้านใน (MM) ปุ่มกระดูก navicular (NT) ข้อต่อระหว่างกระดูกนิ้วของนิ้วโป้ง (IP) และจุดด้านในสุดของรอยพับด้านฝ่าเท้าบริเวณฐานนิ้วโป้ง (MC) ชนิด ตำแหน่ง และการกระจายไปยังนิ้วต่างๆ ของเอ็นเชื่อมต่อระหว่างเอ็นกล้ามเนื้อ FHL และ flexor digitorum longus (FDL) รวมทั้งความยาวของเอ็นกล้ามเนื้อ FHL ที่ได้จากเทคนิค single incision, double incision และ minimally invasive โดยทำการศึกษาจากขาของอาจารย์ใหญ่ชนิดดองสมบูรณ์จำนวน 104 ข้าง และชนิดนิ่มจำนวน 62 ข้าง ผลการศึกษาพบลักษณะทางสัณฐานวิทยาของ MTJ ประเภทที่1 (87.3%) และ 3 (12.7%) ตำแหน่งของ MKH พบว่าอยู่ส่วนต้นของเท้าเมื่อเทียบกับ IP อยู่ส่วนปลายของเท้าเมื่อเทียบกับ MM และอยู่ใต้ต่อ NT โดยมีกลุ่มหลอดเลือดและเส้นประสาท medial plantar วางตัวชิดกับ MKH ตำแหน่งของ MKH บนผิวอยู่ที่ 94.75 ± 8.43% ของความยาวเส้น MC-NT จากจุด MC และต่ำกว่าเส้น MC-NT ด้วยระยะตั้งฉาก 25.11 ± 5.37 มม. พบลักษณะของเอ็นเชื่อมต่อ 3 ประเภท (I, II, V) โดยพบประเภท I (85.4%) ซึ่งมีเอ็นเชื่อมต่อ 1 เส้น จาก FHL ไปยัง FDL มากที่สุด นอกจากนี้ใน 6.1% ของตัวอย่างยังพบรูปแบบใหม่ ซึ่งเอ็นกล้ามเนื้อ FHL แยกออกเป็นสองแขนง แขนงหนึ่งไปยังนิ้วหัวแม่เท้าและอีกแขนงหนึ่งรวมตัวกับเอ็นกล้ามเนื้อ FDL โดยเฉลี่ยตำแหน่งของเอ็นเชื่อมต่อวางตัวอยู่ปลายเท้ากว่าเมื่อเทียบกับ MKH พบการกระจายของเอ็นเชื่อมต่อไปยังนิ้วเท้าทั้ง 4 รูปแบบ ซึ่งรูปแบบ b (67.7%) ที่มีการกระจายไปยังนิ้วชี้และนิ้วกลางเป็นรูปแบบที่พบมากที่สุด ความยาวเฉลี่ยของเอ็นกล้ามเนื้อ FHL ในฝ่าเท้า (in-situ) และเมื่อตัดจากจุดเกาะปลาย (ex-vivo) มีความแตกต่างกันอย่างมีนัยสำคัญทางสถิติในทุกเทคนิค โดยเทคนิค minimally invasive มีความยาวมากที่สุด มีค่าประมาณ 85% (in-situ) และ 83% (ex-vivo) ของความยาวเท้าและมีความสัมพันธ์เชิงบวกระดับปานกลางกับความยาวเท้า ผลการศึกษาครั้งนี้คาดว่าจะช่วยเพิ่มประสิทธิภาพของการผ่าตัดปลูกย้ายเอ็นกล้ามเนื้อ FHL และการผ่าตัดอื่นๆ บริเวณเท้าและข้อเท้ารวมทั้งช่วยลดภาวะแทรกซ้อนที่อาจเกิดขึ้น

สาขาวิชา	วิทยาศาสตร์การแพทย์	ลายมือชื่อนิสิต	
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Perin Wan-ae-loh : QUALITATIVE AND QUANTITATIVE MORPHOLOGICAL STUDY OF FLEXOR HALLUCIS LONGUS IMPLICATED IN TENDON HARVESTING AND TRANSFER. Advisor: Prof. VILAI CHENTANEZ, M.D., Ph.D.

Flexor hallucis longus (FHL) transfer is a widely used technique for reconstruction of Achilles tendinopathies, but the complications such as neurovascular injury and functional loss of toes have been reported. This study aimed to evaluate the morphology of FHL musculotendinous junction (MTJ), location of MKH in reference to the landmarks in foot, type and morphometry of tendinous interconnection between FHL and flexor digitorum longus (FDL) tendons and FHL tendon length in single incision, double incision and minimally invasive techniques. The dissection was performed in 104 embalmed and 62 soft cadaveric feet. The result showed type 1 (87.3%) and type 3 (12.7%) of MTJ morphology. MKH was located proximal to interphalangeal joint of great toe (IP), under navicular tuberosity (NT) and distal to medial malleolus (MM) with medial plantar neurovascular bundle residing closely. Surface localization of MKH from medial end of plantar flexion crease at the base of great toes (MC) was 94.75 ± 8.43% of MC-NT length with a perpendicular distance of 25.11 ± 5.37 mm below MC-NT line. Three types of interconnection (I, II, V) were found. The most frequent type is type I (85.4 %) which had a slip directly from FHL and the mean distance of slip in all type was distal to MKH. In addition, a new type of connection was found in 6.1%. FHL tendon bifurcated into one tendon to the first toe and the other tendon fused with FDL tendon. Four types of slip distribution to lesser toes were defined in this study and type b with a distribution to 2^{nd} and 3^{rd} toes, was the majority. The length of FHL tendon in foot (in-situ) and after it was cut from the insertion (ex-vivo) was longest in minimally invasive technique (83% and 95% of foot length) and it had the moderate positive correlation to foot length. Moreover, there was a significant difference between in situ and ex vivo length in all techniques. In summary, the knowledge of this investigation might be helpful in order to enhance the clinical efficacy of foot and ankle surgery and minimize the potential complications.

Field of Study:	Medical Sciences	Student's Signature ....
Academic Year:	2019	Advisor's Signature ....

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LIST OF ABBREVIATIONS

A	Perpendicular point of MKH on MC-NT line
ABH	Abductor hallucis
FDL	Flexor digitorum longus
FDA	Flexor digitorum accessorius
FDAL	Flexor digitorum accessories longus
FDB	Flexor digitorum brevis
FHB	Flexor hallucis brevis
FHL	Flexor hallucis longus
IP	The first interphalangeal joint of great toe
LPN	Lateral plantar nerve
LPNVB	Lateral plantar neurovascular bundle
MC	Medial end of plantar flexion crease at the base of the great toe
MTP	Metatarsophalangeal joint
MKH	Master knot of Henry
MM	Medial malleolus
MPN	Medial plantar nerve
MPNVB	Medial plantar neurovascular bundle
MTJ	Musculotendinous junction
NT	Navicular tuberosity
QP	Quadratus plantae
ST	Sustentaculum tali
TBNVB	Tibial neurovascular bundle
TP	Tibialis posterior

CHAPTER I

INTRODUCTION

1.1 Background and rationale

Achilles tendinopathy is one of the common overuse disorders with an increasing numbers of patients in all age. It commonly occurs in active and inactive people, especially in individuals who love running or jumping activities [1-3]. Patients normally experience pain and functional impairment which affects their activities of daily living. The progression of this intratendinous lesion can lead to partial or complete rupture of Achilles tendon resulting to the instability and dysfunction of ankle joint [4, 5]. Despite of noninvasive treatments such as physical therapy, orthotics and drugs, the surgical intervention might be necessary when the clinical outcome remains disappointing [1, 3].

Flexor hallucis longus (FHL) transfer is a widely used technique for reconstruction of Achilles tendinopathies [6, 7]. This technique proposes to repair the length, strengthen the injured tendon with additional tendon, and corporate more muscle force to the plantar flexor [1]. FHL is appropriated for transfer because its strength, its axis and amplitude of contraction, and coincident action with triceps surae muscles [8]. Moreover, FHL transfer can also reduce the pain by normalizing vascularity [1, 9]. Furthermore, FHL transfer is also used for the treatment of posterior tibial insufficiency with a good to excellent clinical outcome as well [10, 11].

There are many techniques for harvesting of FHL tendon grafts including single incision, double incision, and minimally invasive techniques [12]. The differences among each technique are the indication and location of incisions. Importantly, the length of harvested tendon from each technique is vastly different [12]. Although, previous reports revealed good results following FHL transfer, but the complication such as serious injury of the distal branches of the posterior tibial artery and nerve, cock-up deformity, and functional loss of toe have been reported [4, 9, 12, 13]. The challenging during tendon harvesting might be resulted from the complexity of structures in ankle and plantar surface of foot including neurovascular bundle, muscles, tendons, and ligaments.

Anatomically, medial and lateral plantar neurovascular bundles reside near the incision line. In consequence, they might be at risk during harvesting. Furthermore, the connections between FHL and flexor digitorum longus (FDL), which have functional importance in toe movement, might restrict harvesting of the FHL tendon distal to the knot of Henry [13]. The previous research suggested that, these interconnections have to be cut when harvesting FHL tendon [12]. Therefore, knowledges of the location of interconnections are important for surgeons to decrease and understand the underlying cause of functional loss of toes [13-15]. The other structure which affects tendon harvesting is Master Knot of Henry (MKH) or Henry's knot. MKH means the intersection area, where the tendon of FDL crosses over the tendon of FHL. It has been used as a surgical landmark for the tendon graft harvesting. The exact anatomical location of MKH remains controversial. Therefore, the precise location of the MKH is needed for the better result [14].

Therefore, comprehension of the length of FHL available for harvesting, the relationship between tendon and neurovascular bundle, the interconnections between FHL and FDL, and the anatomical locations of MKH will help to guide the surgeon to make the decision and decrease the potential morbidity whether a surgeon chooses single incision, double incision or minimally invasive technique [12]. Although, the length of FHL tendon in each technique of FHL harvesting, the interconnections between FHL and FDL and anatomical variations at MKH were reported in previous studies, but almost of them were studied in embalmed cadavers. In addition, the difference between races and ethnics were found [12, 16]. Significantly, the length of FHL tendon after cut for harvesting, which might be different from the length of attached tendon, has not been reported. This anatomical study aimed to clarify these precise anatomical comprehensions in both embalmed and soft cadavers.

1.2 Research Questions

1. How long is the length of FHL tendon harvested from single incision, double incision, and minimally invasive techniques?
2. How many types of the morphology of FHL musculotendinous junction are there in Thai population?
3. What is the relationship between neurovascular bundle and FHL in posterior ankle joint?
4. How to localize MKH by the surface landmarks?
5. What is the relationship between neurovascular bundle and MKH?
6. How many characteristic of the interconnection between FHL and FDL at plantar surface of the foot are there in Thai population?
7. How many types of the contribution of FHL tendon to long flexor tendon of lesser toes are there in Thai population?

1.3 Research Objectives

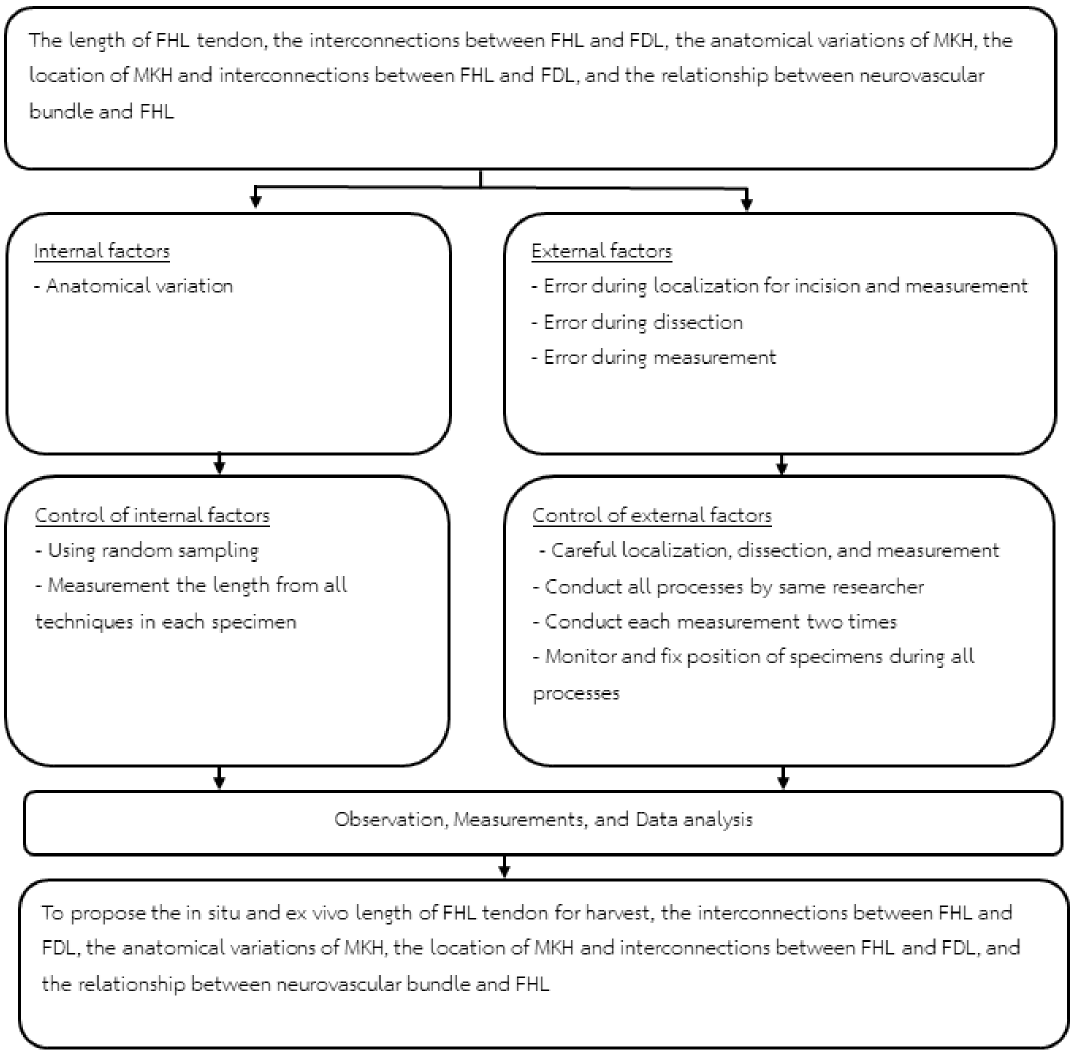
Soft cadavers

1. To measure the in situ length of FHL tendon from single incision, double incision, and minimal invasive techniques of FHL tendon transfer
2. To measure the ex vivo length of FHL tendon from single incision, double incision, and minimal invasive techniques of FHL tendon transfer
3. To classify the types of FHL musculotendinous junction
4. To identify the relationship between neurovascular bundle and FHL at posterior ankle joint
5. To locate the surface landmarks of MKH
6. To examine the anatomical relationship between MKH and plantar neurovascular bundle.
7. To classify the types of interconnection between FHL and FDL at plantar surface of the foot
8. To classify the types of the contribution of FHL tendon to lesser toes

Embalmed cadavers

1. To classify the types of FHL musculotendinous junction
2. To classify the types of interconnection between FHL and FDL at plantar surface of the foot
3. To classify the types of the contribution of FHL tendon to lesser toes

1.4 Conceptual Framework



1.5 Key words

Flexor hallucis longus, Master knot of Henry, Plantar nerve, Surface landmark, Tendon transfer

1.6 Research design

Descriptive research

1.7 Benefits and applications

The benefits of this study are to provide the actual length of FHL tendon, the incidence and patterns of musculotendinous junction of FHL, which can be used by the surgeons to design the appropriate operation technique for individual patient. The precise surface location of MKH and the interconnection between FHL and FDL will be applied for the easier identification of incision site and improve the clinical efficacy of the surgery. The knowledge of communicating between FHL and FDL will give the better understanding of the anatomical function of long flexor tendons of toes, which might be the underlying cause of functional loss of toes after FHL transfer. The relation between tendon and neurovascular bundle will assist the clinician to avoid iatrogenic injury. In conclusion, the knowledge of this investigation might enhance the clinical efficacy of foot and ankle surgery and minimize the potential complications.

CHARTER II
LITERATURES REVIEW

2.1 Anatomy of flexor hallucis longus muscle

Flexor hallucis longus (FHL) muscle is one of the muscles in deep posterior compartment of the lower extremity (Figure 1). FHL is a bi-pennate muscle which originates from the lower two-thirds of posterior surface of fibula, fascia that covers it, interosseous membrane, and intermuscular septum. The muscle fibers of FHL course postero-inferiorly and pass through the tarsal tunnel on medial side of the ankle. FHL resides posterior to tibial neurovascular bundle. The area where the most distal muscle fibers attached the tendon is called the musculotendinous junction (MTJ). MTJ normally resides at the level which FHL enters the flexor retinaculum. It has a tendon sheath that occupies its compartment deep to the retinaculum. FHL tendon runs downward from the fibro-osseous tunnel posterior to talus and passes into the planta. FHL and FDL tendons pierce the medial intermuscular septum from medial to lateral direction to get into the middle compartment of the planta. FHL tendon travels distally superficial to the flexor hallucis brevis (FHB). Then, it traverses between two heads of FHB along with the branch from medial plantar neurovascular bundle and inserts at plantar surface of the base of the great toe's distal phalanx (Figure 1) [7, 17-20].

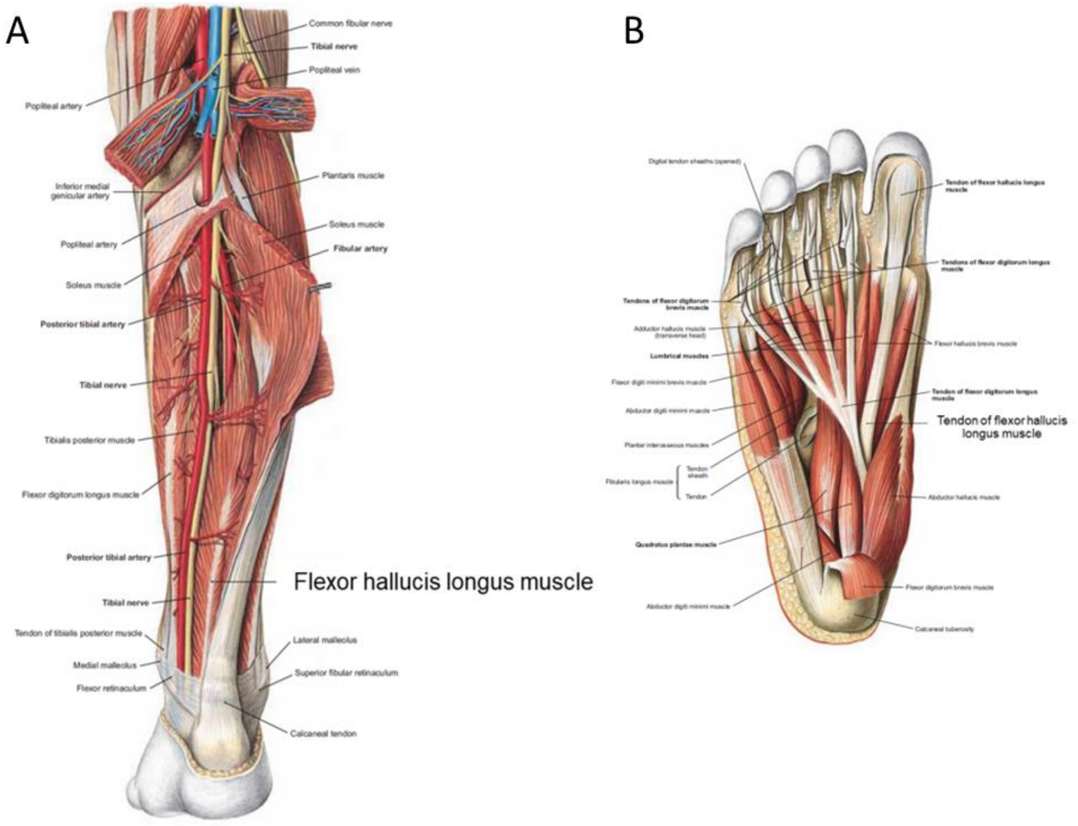


Figure 1 Illustrations of flexor hallucis longus in leg (A) and foot (B) [21]

The course of FHL tendon is divided into three zones (Figure 2). Zone 1 is resided behind the ankle joint. It begins from MTJ to the opening of the tunnel under the sustentaculum tali of calcaneus. The location of zone 2 is starting from the tunnel under the sustentaculum tali to the Master knot of Henry (MKH). MKH is the intersection area, where the tendon of FDL crosses over the tendon of FHL. Lastly, zone 3 is located from MKH to the insertion point of tendon at the base of the distal phalanx [14, 18, 22].

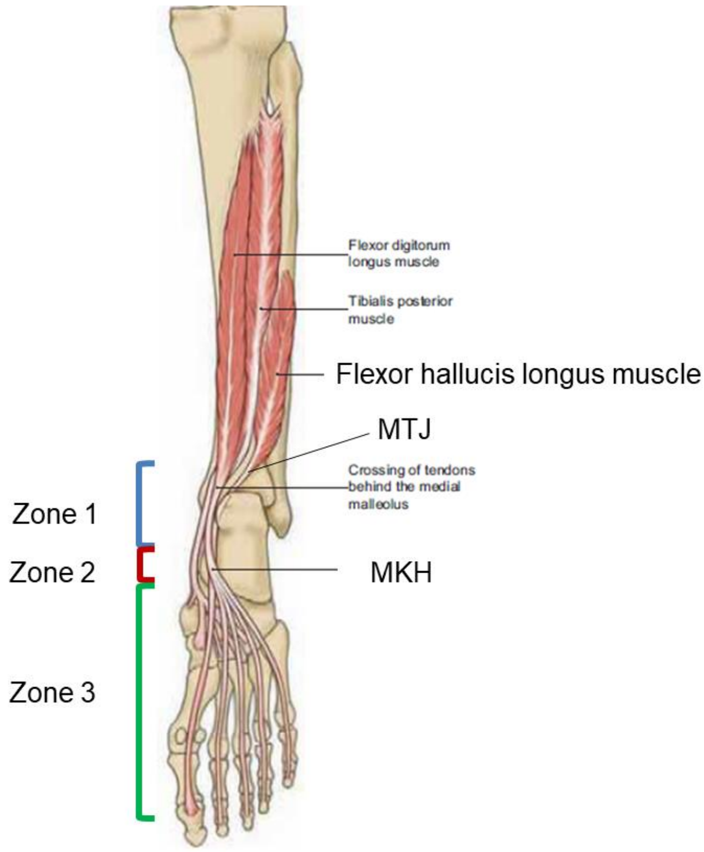


Figure 2 Illustration shows the zones of FHL tendon (modified from Clement D., 2011) [21]

Tibial neurovascular bundle reside medial and close to FHL in the ankle. In the cadaveric study by Mao et al. two patterns were identified regarding the relation between FHL and neurovascular bundle at the level of posterior ankle joint. In Pattern 1, which had the space between FHL tendon and neurovascular bundle, was observed in 94.3% of specimens (Figure 3). The mean distance was 3.46 ± 2.12 mm. The space between FHL tendon and neurovascular bundle was not observed in pattern 2 (Figure 3). This pattern was observed in 5.7% of specimens [23].

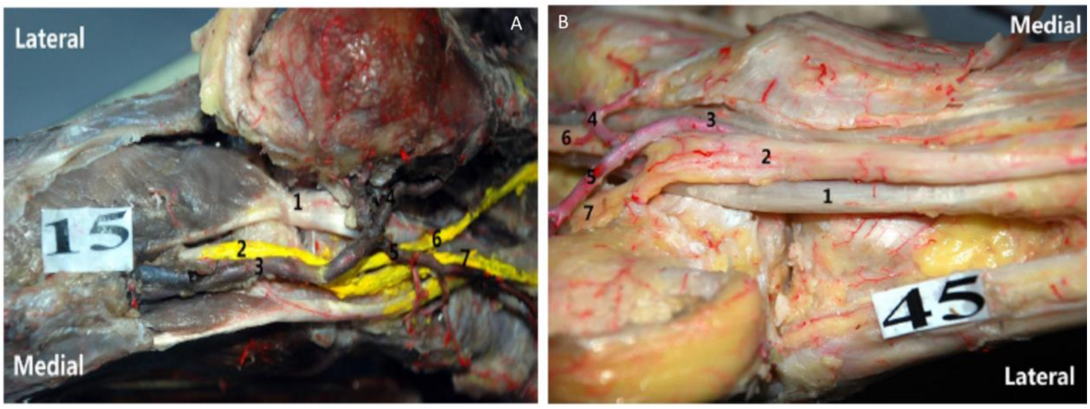


Figure 3 Two patterns of the relationship between FHL and neurovascular bundle at posterior ankle joint; A: type 1, B: type 2 [23].

(1: flexor hallucis longus (FHL), 2: tibial nerve, 3: posterior tibial artery, 4: medial plantar artery, 5: lateral plantar artery, 6: medial plantar nerve, 7: lateral plantar nerve)

In total ankle MRI scans, the mean distance from the FHL tendon to the neurovascular bundle was 1.3 mm. The mean distance between FHL to neurovascular bundle in cases with flexor digitorum accessorius longus muscle (FDAL) was of 1.5 mm (Figure 4).The short distance between FHL and neurovascular bundle means a possible high risk of injury to posterior neurovascular bundle [24].

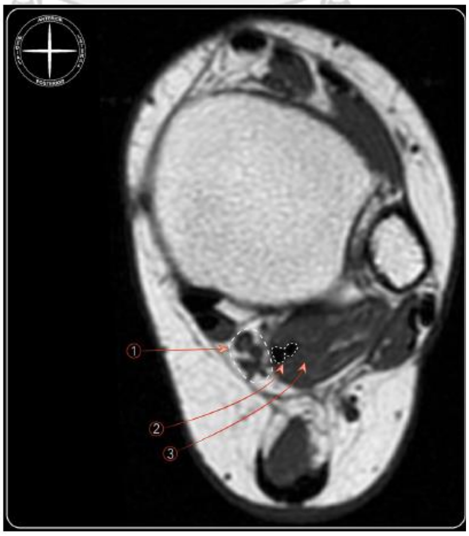


Figure 4 The anatomical relation between FHL tendon and neurovascular bundle in total ankle MRI [24]

(1: posterior tibial neurovascular bundle, 2: tendons of FHL and FDAL. 3: FHL muscle belly)

FHL receives innervation from the tibial nerve which comprises of spinal roots from L4-5 and S1-3 [17, 25]. The arterial supply of FHL is from a muscular branch of the peroneal portion of the posterior tibial artery. The venous return of this muscle is through the peroneal vein, which is a branch of the popliteal vein. The lymphatic drainage of FHL is the popliteal lymph nodes, which drain to the deep and superficial inguinal nodes [25].

The function of FHL is to assist other deep muscle of posterior compartment of leg in plantar flexion, inversion and supination of the foot. The unique function of FHL is great toe flexion through plantar flexion of talocrural joint, metatarsophalangeal and interphalangeal joints of the great toe [17, 18, 26].

Morphological variation of FHL

There are many reports regarding the variation of FHL morphology observed during performing FHL transfer. However, a specific study of MTJ anatomical variations is lacking (Table 1) [7].

Pichler et al. (2005) studied the morphology of MTJ and distance from MTJ to the bone cartilage transition of tibia (measuring point) [7]. They reported three types of MTJ (Figure 5). The description of each type is the following:

Type 1: the medial muscle belly reached more proximally than the lateral belly (70 cases, 88%) (Figure5 a)

Type 2: the medial and lateral muscle bellies had equal length (3 cases, 4%) (Figure 5 b).

Type 3: the medial muscle belly reached more distally than the lateral muscle belly (5 cases, 6%) (Figure 5 c).

Other morphology: only lateral muscle belly (2 cases, 3%).

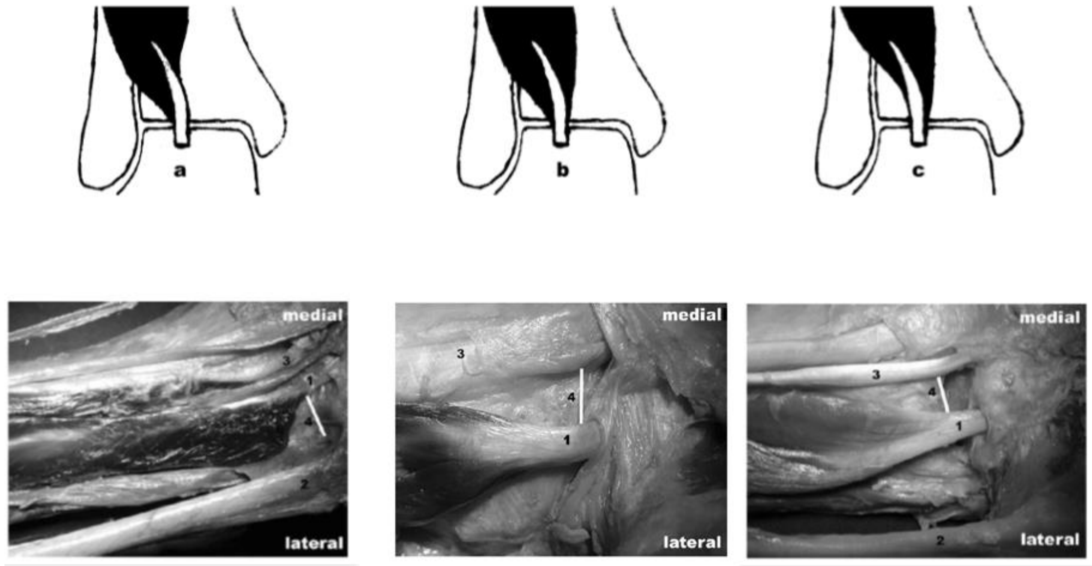


Figure 5 Three type of MTJ morphology in the study of Pichler et al., (7)

(1:tendon of flexor hallucis longus, 3: Achilles tendon, 4: bone–cartilage transition of tibia)

According to the distances between MTJ and the measuring point, there were the cases whose FHL ended proximal or distal to measuring point (Figure 6). The lateral muscle belly ended between 57 mm proximal and 25 mm distal to the measuring point with the total range of 82 mm. Regard to the medial muscle belly, it ended between 114 mm proximal and 5.5 mm distal to the measuring point with the total range of 119.5 mm. In summary, the average distance of the medial muscle belly is 34.64±22.79 mm and the lateral muscle belly is 1.48±12.92 mm from measuring point.

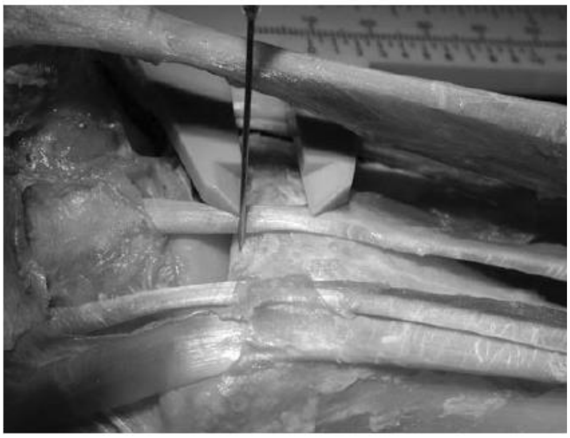


Figure 6 The measuring point is marked with a needle, and the distance between MTJ and this point is measured [7].

In 2018, there was another report from Mao et al., [23]. They classified MTJ of FHL based on the criteria from Pichler et al. [7]. Three types of MTJ morphologies were observed (Figure 7). Type 1 was also the most frequent observed in 63 cases (90%). Type 2 was found in five specimens (7.1%). Type 3 was identified in two cases (2.9%). There was no other variation [23]. They also reported the distance from MTJ and the measuring point. However, the measuring point, which was named as zero point was referred to the crossing of distal osseous part of tibia and FHL tendon. They found that the medial muscle belly ended at 33.24±1.5 mm proximal to the measuring point (range = +115 to -8 mm, total range = 123 mm) and the lateral muscle belly ended at 3.14±2.2 mm proximal to the measuring point (range = +39 to -43 mm, total range = 82 mm). There was no statistically significant difference between genders and sides.

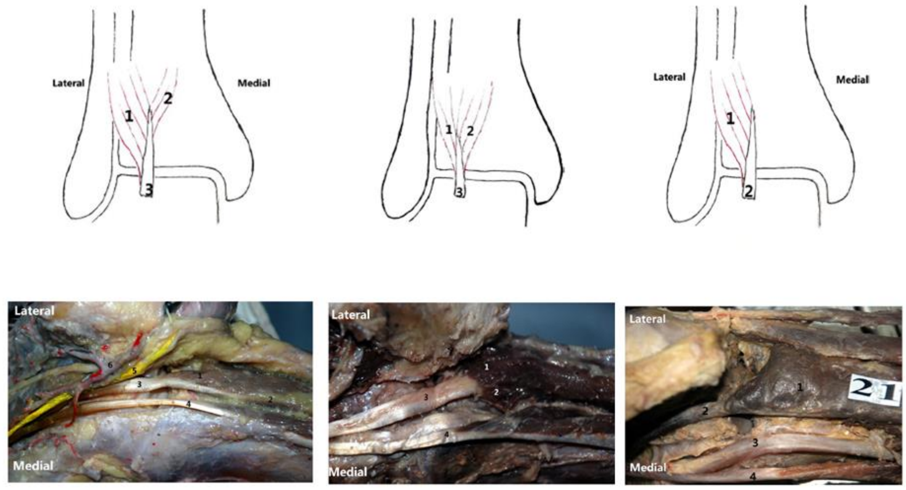


Figure 7 Three types of MTJ morphology in the study of Mao and coworkers [23]
(1: Lateral muscle belly of FHL, 2: medial muscle belly of FHL, 3: FHL tendon, 4: FDL tendon, 5: plantar nerve, 6: posterior tibial artery)

Table 1 Type of MTJ and the distance from the measuring point [7, 23]

Author	Year	Race/Ethnic	Cadaveric type	n	MTJ morphology (side, %) Type 1	Type 2	Type 3	Other
Mao et al. [23]	2018	Asian	embalmed	70				
• Prevalence					63 (90%)	5 (7.1%)	2 (2.9%)	0 (0%)
• Distance from MTJ and the crossing of distal osseous part of tibia and FHL tendon								
- Medial belly (mm)					33.24±1.5			
- Lateral belly (mm)					3.14±2.2			
Pichler et al. [7]	2005	-	embalmed	80				
• Prevalence					70 (88%)	3 (4%)	5 (6%)	2 (3%)
• Distance from MTJ to the bone cartilage transition of tibia								
- Medial belly (mm)					+114	+10	+32	-
- Lateral belly (mm)					+26	+10	+57	-

+: proximal to measuring point- : distal to measuring point

(MTJ: musculotendinous junction)

Knowledge of morphological variation of the FHL muscle is useful for operative planning. For example, FHL tendon transfer is used to manage Achilles tendon gap because it is a safe and trust worthy method with enhanced functional outcome. Previous study reported that, Achilles tendon ruptures mostly happen approximately 2–6 cm proximal to its insertion due to the vascular supply in this area is reduced. The tendon transfer improves the vascular supply in this area and covers the soft tissue defects. If FHL muscle bellies are adequate to cover the tendon defect, the other combining techniques are not necessary. Consequently, knowledge of MTJ anatomical variation is essential in designing the operation of FHL transfer. Moreover, these anatomical variations should be aware in interpretation of MRI or ultrasound in this area [7, 23].

2.2 Master knot of Henry

"Master Knot of Henry or Henry's Knot" (MKH) is firstly identified by Henry in 1995. MKH refers to the intersection area, where the FDL tendon crosses over the FHL tendon in the mid-foot at the level of the navicular bone [10, 14, 20]. Henry described the knot as the tying of FHL and FDL tendons to the inferior part of the summit of the vault of the foot, with the origin of FHB assisting in their suspension. At the crossing point, the FDL tendon places superficially oblique (plantar) to the FHL tendon (Figure 8) [10].

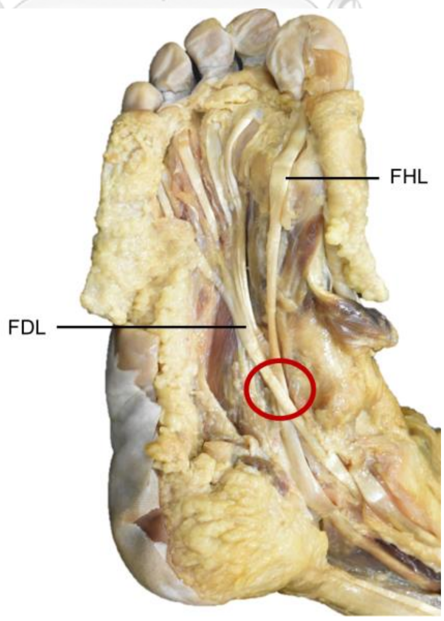


Figure 8 Plantar surface of the foot demonstrating Master Knot of Henry or MKH (red circle).

(FDL: flexor digitorum longus, FHL: Flexor hallucis longus)

Anatomical location of MKH

MKH has been widely utilized as a surgical landmark for the FHL tendon graft harvesting especially in double incision technique. For effective surgical outcome, the exact anatomical location of MKH should be aware. However, this important information remains controversial [14]. Further studies about the accurate location of the MKH are intensely needed.

The location of MKH was studied by Mao et al. in 2014. Sixty-four legs from 32 embalmed cadavers were analyzed. The result showed that, MKH was resided at 10.89±1.08 cm proximal to first interphalangeal joint and 2.21±0.34 cm inferior to the navicular tuberosity (Figure 9, Table 2). Beger et al. further investigated the precise location of the MKH in 2018 [14]. Twenty feet of ten formalin fixed cadavers in Turkish population were studied. The distance of MKH to medial malleolus (MM), navicular tuberosity (NT) and first interphalangeal joint (IP) were analyzed (Figure 9). The distance between MKH and MM, NT and IP were 5.93±0.74 cm, 1.75±0.39 cm and 12.61±1.11 cm respectively. When comparing the results of Mao and Beger, the exact location of MKH was different (Table 2).

Table 2 Distances from MKH to anatomical landmarks [12, 14]

Authors	Year	Race/ Ethnic	Cadaveric type	n	Anatomical landmarks (cm) mean±SD (min-max)		
					MM	NT	IP
Beger et al. [14]	2018	Tukish	Formalin fixed	20	5.93±0.74 (4.72-7.35)	1.75±0.39 (1.11-2.44)	12.61±1.11 (10.33-14.09)
Mao et al. [12]	2015	Asian	Embalmed	64	-	2.21±0.34 (1.59–3.04)	10.89±1.08 (13.04–9.22)

(IP: the first interphalangeal joint, MM: medial malleolus, NT: navicular tuberosity)

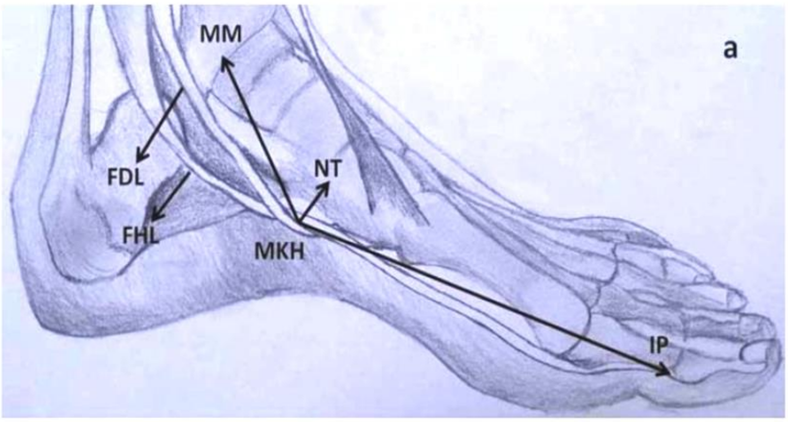


Figure 9 Illustration showing measuring of distances from MKH to medial malleolus (MM), navicular tuberosity (NT) and first interphalangeal joint (IP) [12].

The relationship between MKH and plantar nerves

Anatomically, medial plantar nerves (MPN) travel along the plantar surface of FDL tendon and passes through MKH. Then, it goes on the medial border of the foot and give branches to medial and lateral sides [15]. The anatomical relationship between the plantar nerves and MKH was reported by Mao et al. in 2017 [16]. The relationship was classified into two patterns. In pattern 1, which was identified in 94.1% of specimens, the mean distance between MPN and MKH was 5.96±1.12mm (Figure 10 Left). In pattern 2, there was no distance between MPN and MKH. This pattern was observed in 5.9% of specimens (Figure 10 Right). The mean distance between the MPN and MKH was 5.26 mm. According to lateral plantar nerve (LPN), it showed a distance of 15.5±4.2 mm from MKH.

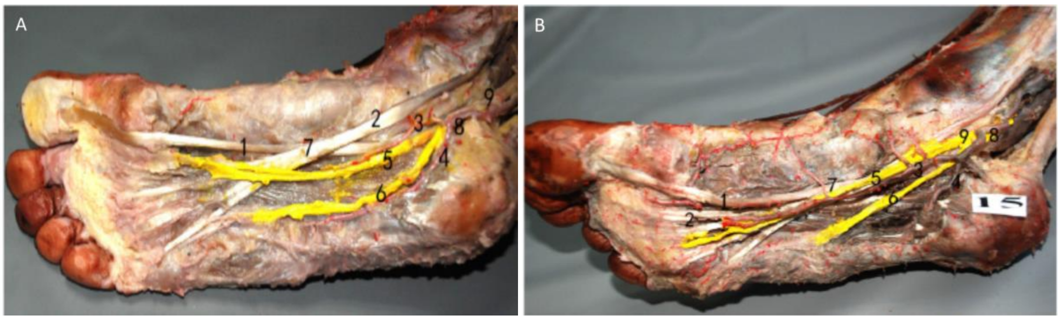


Figure 10 The relationship between MPN and MKH in pattern 1 (A) and pattern 2 (B) (16)

(1: flexor hallucis longus (FHL), 2: flexor digitorum longus (FDL), 3: medial plantar nerve (MPN), 4: lateral plantar nerve, 5: medial plantar artery, 6: lateral plantar artery, 7: master knot of Henry (MKH), 8: posterior tibial artery, 9: tibial nerve)

2.3 Tendinous interconnection between FHL and FDL

Beside of the intersection of FHL and FDL tendon in MKH, the tendinous slip between FHL and FDL tendons is another relationship. The tendinous interconnects from the FHL tendon to the FDL tendon is located distal to MKH (Figure 11). This slip usually passes to the tendon divisions of lesser toes [27].

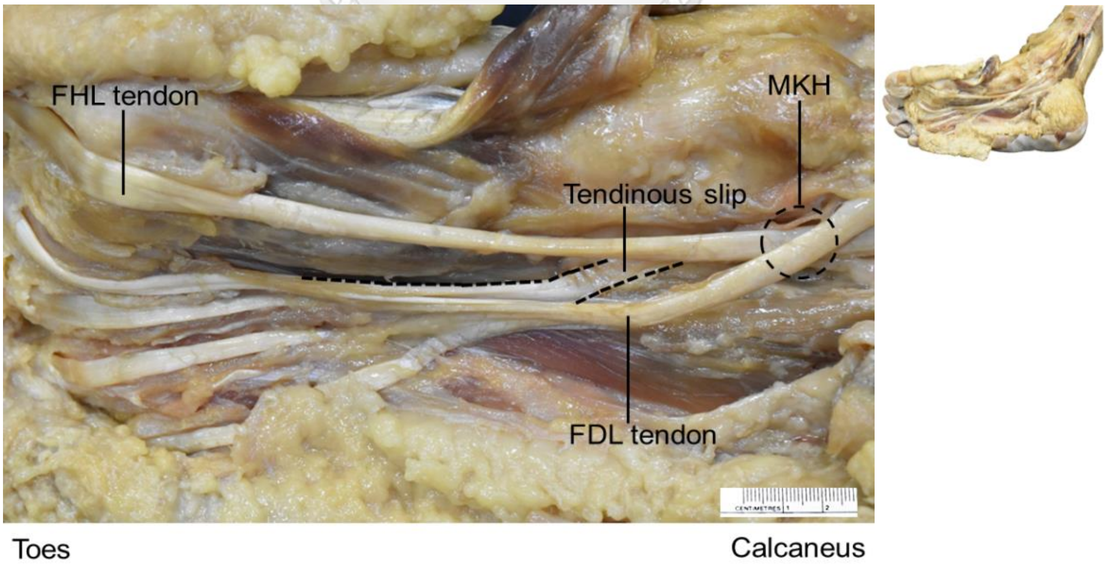


Figure 11 Plantar surface of right foot showing tendinous interconnection between FHL and FDL tendon.

(FDL: flexor digitorum longus, FHL: Flexor hallucis longus, MKH: master knot of Henry)

Various forms of the tendinous slips were reported previously (Table 3). Martin (1964) dissected thirty-three adult human feet. Most specimens (29, 88%) showed the interconnection between FHL and FDL tendon. Only 2 specimens (6%) did not have interconnection between FHL and FDL. Moreover, the FHL and FDL tendons gave a slip to each other in two specimens [27].

In 1994, eighty-five feet of embalmed cadavers were obtained for anatomical analysis of this interconnection by Wapner et al. [28]. Most cadaveric feet had tendinous interconnection between long flexors (83, 98%). 67% had a slip from FHL to FDL tendons, while 31% had the slips connect to each other. Absence of connection was found in two feet (2%). The tendinous interconnection sprang from the fibular side of the FHL and proceeded toward the forefoot, where it splayed into one or more separable lesser toe tendons.

O'Sullivan et al. (2005) conducted a study in sixteen embalmed cadaveric feet [10]. Three pattern of interconnection were described. The first pattern, which showed in 11 specimens, was the present of tendinous fibers directed from FHL to FDL tendons (Figure 12 A). The tendinous slip which directed from FDL to FHL was classified as pattern 2 (Figure 12 B). Two specimens were found in this pattern. Pattern 3 showed a tendinous slip directed from FDL to FHL tendon and an additional tendinous slip connected from FHL to FDL tendon. Three specimens were classified in this type (Figure 12 C).

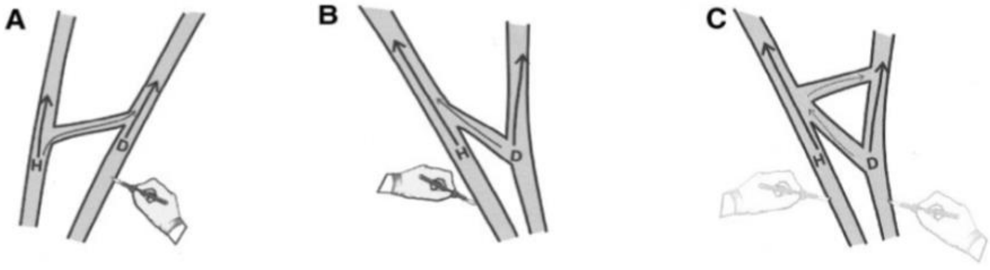


Figure 12 The illustration showing pattern of tendinous interconnection between FHL (H) and FDL (D) tendons from the study of O'Sullivan and coworkers [10]

(FDL: flexor digitorum longus, FHL: flexor hallucis longus, QP: quadratus plantae)

LaRue et al. (2006) conducted a study in twenty-four Caucasians cadaveric legs [29]. Twenty legs were from fresh cadavers and four from embalmed cadavers. Three different configurations of interconnection between FHL and FDL tendon were found (Figure 13). The proximal attachment branching from the FHL to the FDL tendon was sorted into type 1 (10, 42%). Type 2 had proximal attachments branching from FHL to FDL tendon and from FDL tendon proximally to FHL tendon (10, 42%). The cases which had no attachment were organized into type 3 (4, 17 %).

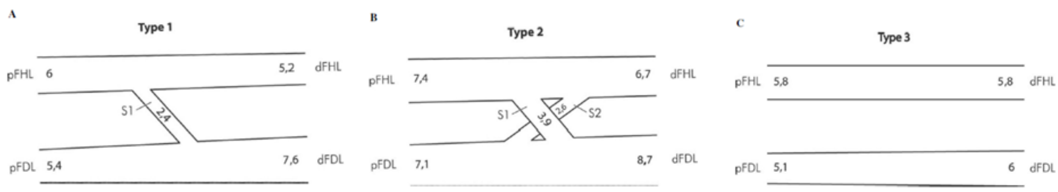


Figure 13 The illustration of tendinous interconnection patterns between FHL and FDL tendon from the study of LaRue and coworkers [29]

(FDL: flexor digitorum longus, FHL: flexor hallucis longus)

Mulier et al. (2007) investigated the tendinous interconnection in 24 specimens (5 fresh frozen and 19 embalmed cadaveric feet) [15]. Twenty one specimens showed interconnection between tendons. A single tendinous slip directed from FHL to FDL tendon was observed in 14 specimens (58%). Double slips, which directed from FHL to FDL tendon and from FDL to FHL, were identified in 7 specimens (29%).

In 2013, Plaass et al. analyzed the interconnection in 60 embalmed feet from 30 cadavers [30]. Modified classification system was used to analyze the interconnections (Figure 14). A proximal to distal interconnection from FHL to FDL tendons was shown in 58 specimens (97%). Forty feet (67%) were types I, which had a tendinous slip branched proximally from FHL to FDL tendon. Eighteen feet (30%) were types III. Type III had the proximal to distal connection from the FHL to the FDL and a connection from the proximal FDL to the distal FHL. Two feet (3%) was type II, which had a proximal FDL to distal FHL interconnection.

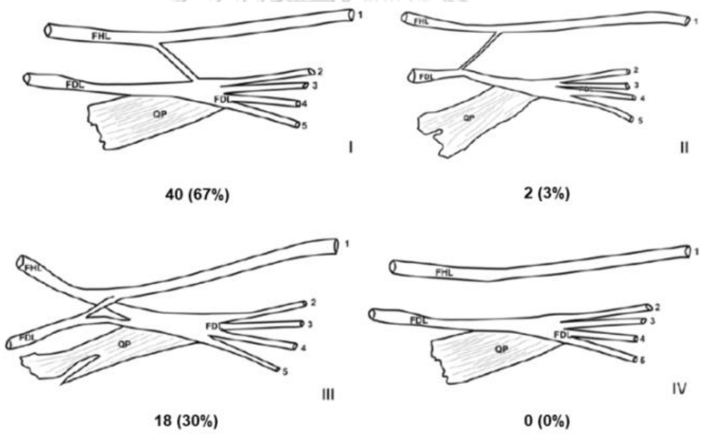


Figure 14 Modified classification system for tendinous interconnection between FHL and FDL by Plaass et al.[30].

(FDL: flexor digitorum longus, FHL: flexor hallucis longus, QP: quadratus plantae)

The tendinous interconnection between FHL and FDL tendon from sixty-four embalmed cadaveric legs were analyzed by Mao et al. in 2015 [12]. The interconnection was classified into four types (Figure 15), but only two types of relationship were identified (Figure 16). Sixty two legs was type I (96.9%). Type I was described as a proximal tendinous slip branching from FHL to FDL tendon. Two legs were type II (3.1%). Type II showed two tendinous slips, one slip from FHL proximally to FDL tendon and another slip from FDL proximally to FHL tendon.

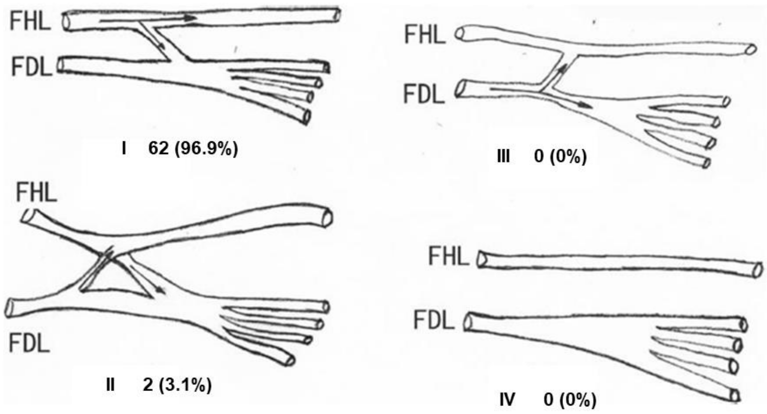


Figure 15 Four types of interconnection was classified by Mao et al. [12].

(FDL: flexor digitorum longus, FHL: flexor hallucis longus)

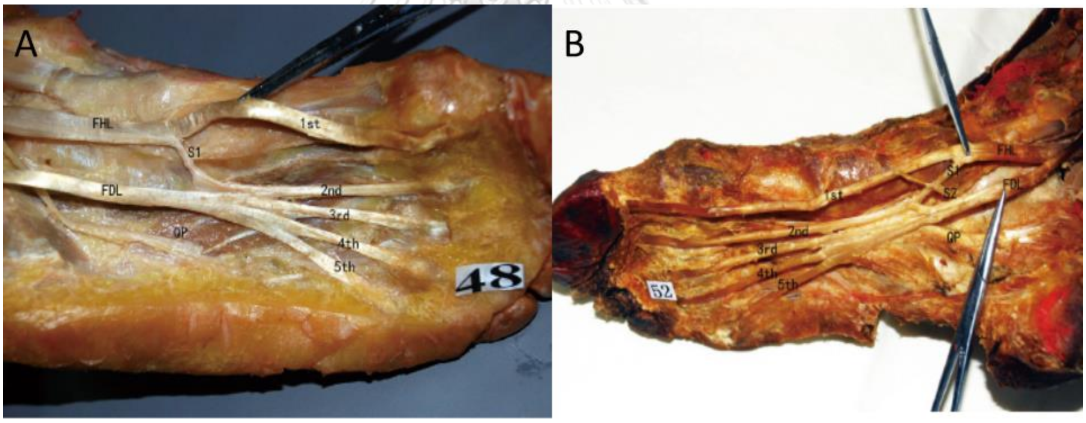


Figure 16 Photographs of interconnections between FHL and FDL tendons in Type I: a slip from the FHL to the FDL tendons (A) and type II: crossed connection between FHL and FDL tendons (B) [12].

(FDL: flexor digitorum longus, FHL: flexor hallucis longus)

In 2016, Edama and colleagues studied tendinous interconnection between FHL and FDL tendon in 100 legs from 55 cadavers [25]. They classified the tendinous interconnection according to O'Sullivanet et al. and Plaass et al. [10, 30]. Eighty six legs (86%) were type I. Type II was identified in 3 legs (3%). Interestingly, eleven legs

(11%) had double slip from FHL to FDL tendons. This type of connection was classified as Type V. Type V was a new type that had not been reported in the previous studies (Figure 17).

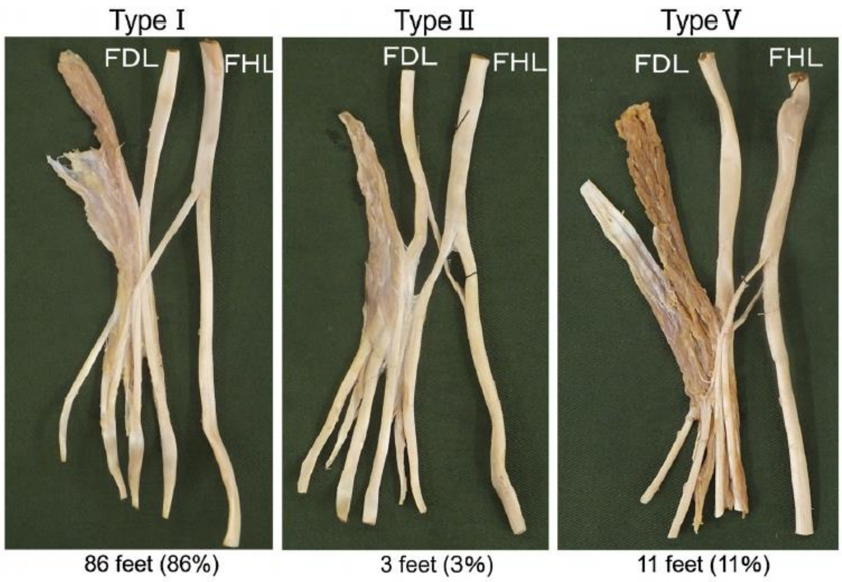


Figure 17 Types of tendinous interconnection between FHL and FDL in the study of Edama et al. [25].

(FDL: flexor digitorum longus, FHL: flexor hallucis longus)

Beger et al. (2018) also considered tendinous interconnection between FHL and FDL in twenty feet of ten formalin fixed cadavers from Turkish population [14]. The tendinous interconnection was classified into 7 types (Figure 18). Fourteen feet (75%) were found to be type 1. Type 2 was shown in 2 feet (10%). Type 3 and 4 were not found in their study. Type 5 was found in 1 foot (5%) as well as type 6 and 7.

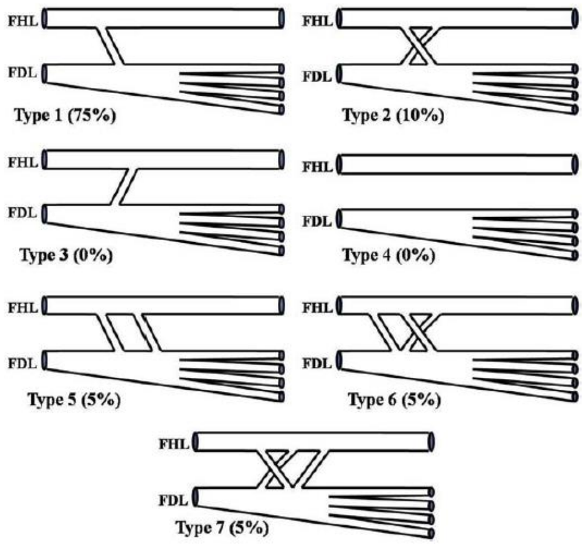


Figure 18 Seven types of the tendinous interconnection in the study of Beger et al. (14)

(FDL: flexor digitorum longus, FHL: flexor hallucis longus)

Table 3 Prevalence of tendinous interconnection between FHL and FDL tendons (classification according to Beger et al.) [10, 12, 14, 15, 25, 27-29, 31]

Author	Year	Race / Ethnic	Cadaveric type	n	%						
					Type I	Type II	Type III	Type IV	Type V	Type VI	Type VII
Vasudha et al. [31]	2019	Indian	Formalin fixed	36	61	2.94	7.35	14.70	8.82	0	1.47
Beger et al. [14]	2018	Turkish	Formalin fixed	20	75	10	0	0	5	5	5
Edama et al. [25]	2016	Asian	Formalin fixed and alcohol	100	86	3	0	0	11	0	0
Mao et al. [12]	2015	Asian	Embalmed	64	96.9	3.1	0	0	-	-	-
Plaass et al. l [30]	2013	Caucasian	Embalmed	60	67	3	30	0	-	-	-
Mulier et al. [15]	2007	-	Fresh Embalmed	20 4	58	29	0	13	-	-	-
LaRue et al. [29]	2006	Caucasian	Fresh Embalmed	5 19	42	42	0	17	-	-	-
O'Sullivan et al. [10]	2005	-	Embalmed	16	68	13	19	0	-	-	-
Wapner et al. [28]	1994	-	Embalmed	85	67	31	-	2	-	-	-
Martin [27]	1964	-	Embalmed	33	88	6	0	6	-	-	-

(FDL: flexor digitorum longus, FHL: flexor hallucis longus)

Interconnections between FHL and FDL are important for tendon harvesting [30].The benefit of these connections is acting as a natural tenodesis while harvesting FHL tendon grafts proximal to MKH [29]. On the other hand, it is a critical disadvantage that affects tendon harvesting. The connections between FHL and FDL tendon, which have functional importance in toe movement, might restrict harvesting of the FHL tendon distal to MKH [13]. To harvest the longer tendon beyond MKH, minimally invasive technique is performed [12, 30]. With this technique, the interconnection between FHL and FDL must be cut with an additional incision by medial or direct plantar approach. Mao et al. proposed that the incision line should start from MKH and extends distally [12]. Therefore, the locations of interconnection are necessary to be investigated. Mostly, the interconnections between these tendons locate distal to MKH and proximal to FDL tendon division [14, 32]. Beger et al. (2018) suggested that, the interconnection from FHL to FDL could be cut at an average of 2.71 cm distal to the MKH and that from FDL to FHL could be cut at an average of 2.71 cm proximal to FDL tendon division [14]. Moreover, distance from anatomical landmarks including medial malleolus (MM), navicular tuberosity (NT) and first interphalangeal joint (IP) were used to locate the interconnection between FHL and FDL tendons (Table 4) [14, 30, 32].

Table 4 Distance between anatomical landmarks and tendinous interconnection of FHL and FDL tendons [14, 30]

Authors	Year	Race / Ethnic	Cadaveric type	n	Anatomical landmarks (cm) mean±SD (min-max)		
					MM	NT	IP
Beger et al. [14]	2018	Turkish	Formalin fixed				
- S1 proximal point				19	5.89 ± 1.08 (35.98-80.33)	1.84 ± 0.53 (1.05-2.88)	12.39 ± 1.10 (9.99-14.38)
- S1 distal point				19	8.08 ± 1.31 (5.30-10.61)	9.88 ± 0.89 (8.43-12.40)	3.48 ± 1.20 (1.19-5.15)
- S2 proximal point				4	5.05 ± 0.95 (4.37-6.52)	12.54 ± 1.44 (10.38-13.56)	1.78 ± 0.69 (1.01-2.72)
- S2 distal point				4	6.56 ± 0.80 (5.56-7.52)	10.55 ± 1.42 (8.59-12.24)	1.98 ± 0.60 (1.57-2.99)
Plaass et al. [30]	2013	Caucasian	Embalmed	60			
- FHL to FDL					-5.3 ± 1.2 (2-8)	-2.1 ± 0.7 (0-4)	-
- FDL to FHL					-4.6 ± 1.8 (3.5-7.0)	-1.6 ± 0.6 (1-3)	

(S1: slip from FHL to FDL, S2: slip from FDL to FHL)

The characteristic of slips distribution to lesser toes was classified into 4 types (Figure 19) [14]. In type a, the interconnection distributes to 2nd toe. Type b and c are described as distribution of the slips to 2nd-3rd toes and 2nd- 4rd toes respectively. Type d has the distribution of slip to all lesser toes (2nd - 5th toes). The distributions of interconnection slips to lesser toes in each type were described previously (Table 5).

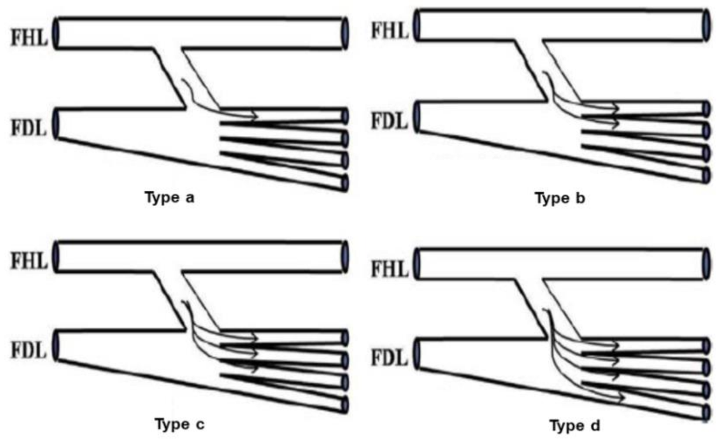


Figure 19 Four types of the slip distribution to lesser toes (modified from Beger et al., 2018) [14]

Table 5 Prevalence of the distribution of tendon slip from FHL to the lesser toes [12, 14, 25, 28, 30, 33]

Author	Year	Race / Ethnic	Cadaveric type	n	Type a (%)	Type b (%)	Type c (%)	Type d (%)
Beger et al. [14]	2016	Turkish	Formalin fixed	20	33	55	7	0
Edama et al. [25]	2016	Asian	Formalin fixed and alcohol	100	31	61	8	0
Mao et al. [12]	2015	Asian	Embalmed	64	31	61	8	0
Plaass et al. [30]	2013	Caucasian	Embalmed	60	67	3	30	0
Hur et al. [33]	2011	Korean	Embalmed	100	8	64	28	0
Wapner et al. [28]	1994	-	Embalmed	85	41	47	9	-
LeDouble [28]	1897	-	-	-	32	58	10	0
Testut [14]	1884	-	-	-	22	40	36	2

The studied method was different between each study. Edama and coworkers removed FHL, FDL, quadratus plantae (QP), and lumbrical muscle from sole of foot. The method of analysis was done by separating FHL from QP and the tendons extending to the lesser toes respectively (Figure 20) [25].

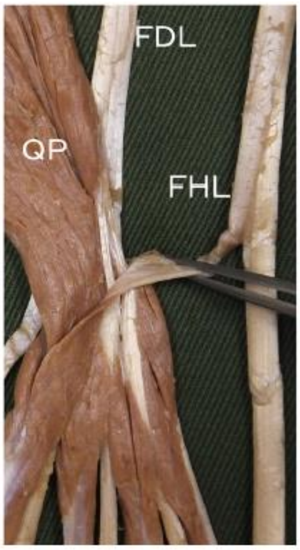


Figure 20 FHL was separated from quadratus plantae, and the tendons extending to the lesser toes for study the distribution of tendinous slip [25].

(FDL: flexor digitorum longus, FHL: flexor hallucis longus, QP: quadratus plantae)

The method of Edama et al. was resembled to Hur et al. [33]. Hur et al. cut FHL and long flexor tendons at the ankle joint and metatarsophalangeal joints respectively. Then, these structures were reflected posteriorly to reveal the tendinous slips distribution (Figure 21).

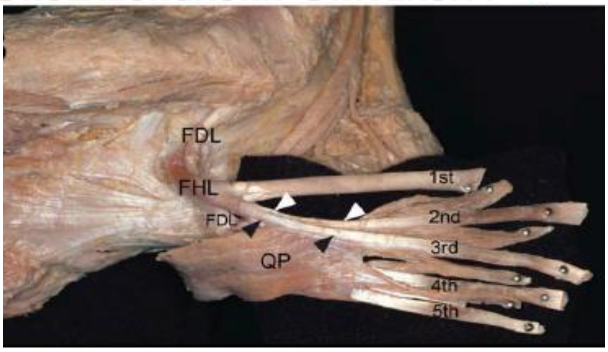


Figure 21 The FHL and long flexor tendons were cut reflected to reveal the tendinous slips distribution **[33]**.

(FDL: flexor digitorum longus, FHL: flexor hallucis longus, QP: quadratus plantae)

O'Sullivan et al., Mao et al., and Plaass et al. used the same method to analyze the functional insertion of the tendinous interconnections. They manually applied the tension to FHL or FDL tendon individually proximal to MKH and the movement of the toe was recorded [10, 12, 30]. Nevertheless, Mao et al. and Plaass et al. classified the distribution of slip into subdivision of tendinous interconnection type that resembled to other studies.

Knowledge of the tendinous interconnections is important for minimizing the functional loss in post-operative period and understanding the underlying cause of functional loss of toes. Nevertheless, anatomical knowledges of interconnections from previous studies are not concordant. In this regard, further studies are required.

2.4 Flexor hallucis longus tendon transfer

FHL tendon is the common tendon used in the augmentation of the Achilles tendon because it is easy to harvest and provide excellent outcomes. It has been used in reconstruction of both chronic Achilles tendinopathy and Achilles tendon ruptures. Augmentation of Achilles tendon with FHL tendon transfer resulted in a good functional outcome and pain relief [1, 34, 35].

The advantages of FHL tendon transfer are the followings [1].

1. The average length of FHL tendon graft is about 8 -10cm with 4 - 5 mm wide, which is adequate for augmentation of Achilles tendon [28, 36].
2. The long muscle belly of the FHL is a good vascular tissue for the hypovascular region of Achilles tendon. This leads to the good unification of FHL into Achilles tendon [37, 38].
3. FHL is the strongest plantar flexor next to the triceps surae [39].
4. Axis of contractile force of FHL is closest to Achilles tendon [40].

5. Neuromuscular activation of FHL is in phase with triceps surae. Thus, it supports the normal gait cycle, particularly for plantar flexion during push-off.

6. FHL tendon is easy to harvest with small risk of neurovascular bundle injury [35].

7. The tendinous interconnections between FHL and FDL tendon allow some flexion of great toe interphalangeal joint by the tenodesis effect after transection of FHL tendon [41].

Results of FHL tendon transfer are good to excellent regardless of the technique used to harvest the tendon. Biomechanical studies showed a little change of pressure under the first or second MTP joint and no functional impairment after operation [34].

Surgical techniques in FHL tendon transfer

- Hansen technique (Single posterior medial incision technique) [41, 42]

The medial incision is made proximally extend 10-12 cm to superior border of the calcaneus. The incision is deepened to expose the anterior aspect of the Achilles tendon. A longitudinal incision is made along the anterior part of paratenon (Figure 22 A). Then, the deep fascia which encloses the deep posterior compartment of leg is opened to expose the muscle belly of FHL in lateral side and neurovascular bundle in medial side. The FHL are transected and pulled as distal as possible with maximum plantar flexion of ankle and great toe (Figure 22 B-C). The muscle belly of FHL is moved posteriorly and separated from the attachment at fibula. FHL is sutured into the anterior portion of Achilles tendon while it held in physiologic tension. Depending on the condition of Achilles tendon and the thickness of soft tissue, FHL tendon is sutured at distal end of Achilles tendon if the attachment of Achilles tendon is intact. In the other hand, if the tendon attachment avulses, FHL tendon is pull through inserted into a drill hole in the medial tubercle of calcaneus (Figure 22 D). The muscle belly of the FHL which extends along the full length of the Achilles tendon, can give the blood supply to Achilles tendon and providing contractile force to increase the strength of triceps surae.

Hansen reported that the existing interconnection between FHL and FDL is sufficient to maintain the strength of great toe plantar flexion.

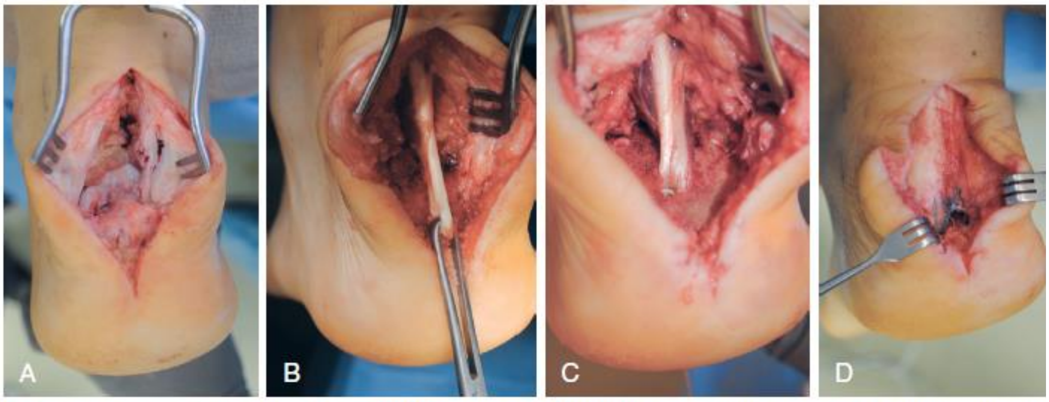


Figure 22 The longitudinal posterior medial incision is created on Achilles tendon (A) and FHL tendon is also pulled through this incision and inserted at calcaneus (B-D)[34].

- Wapner technique (Double incision technique)[35]

The patient is set in supine position. Above the level of abductor hallucis muscle (ABH), a longitudinal incision is made from the navicular to the head of the first metatarsal parallel to the medial edge of midfoot (Figure23). ABH and FHB are moved to plantar side. Anatomical structures in deep surface of midfoot are exposed (Figure 24). FHL and FDL tendons which are generally covered by fatty tissue are identified in this area.

Figure 23 The incision line at midfoot and medial border of Achilles tendon[35]

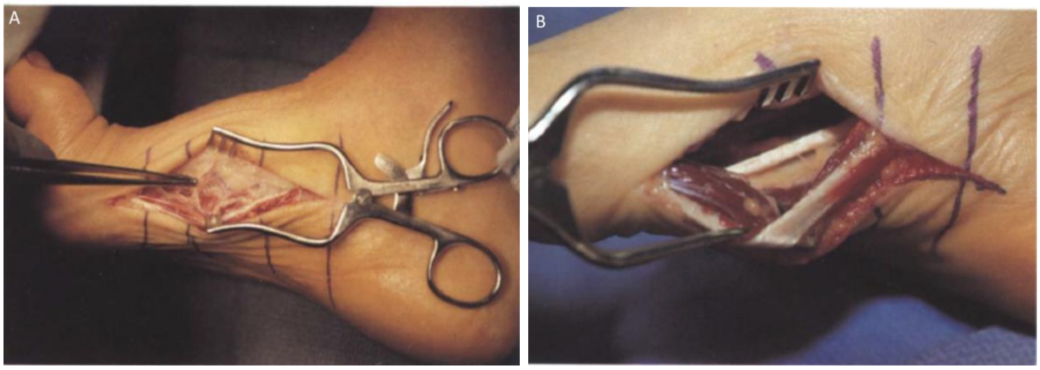


Figure 24 Superior border of Abductor is identified in midfoot incision (A). FHL tendon is exposed after ABH and FHB are moved to plantar side (B) [35].

The dissection can be carried distally to identify FHL and FDL tendons in medial and lateral side. In this area, FDL tendon crossed FHL tendon at MKH. FHL tendon is divided into two parts as distally as possible. The proximal part of FHL is tagged with suture. During all toes is in a neutral position, the distal part of FHL is stitched with FDL, thus FDL provides flexion to all toes (Figure 25).

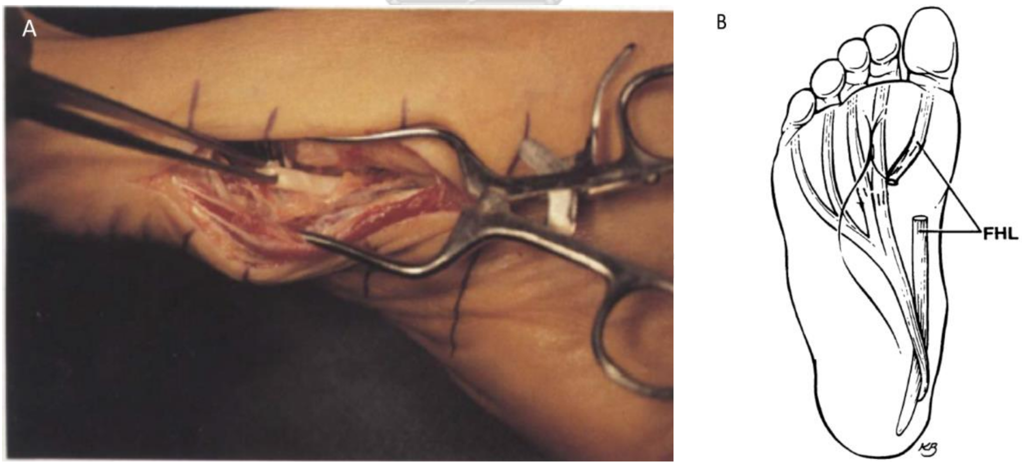


Figure 25 FHL is retracted and transected (A) and the distal part of FHL is sewn with FDL (B) [35].

A longitudinal incision is posteriorly made along the medial border of Achilles tendon from the level of MTJ and extending 1 inch inferior to its insertion. The paratenon is longitudinally opened, and the tendon is examined. Then, the longitudinal incision is made at the fascia that covers posterior compartment of leg, and FHL is identified. The tendon is pulled from the midfoot to the posterior incision (Figure 26).

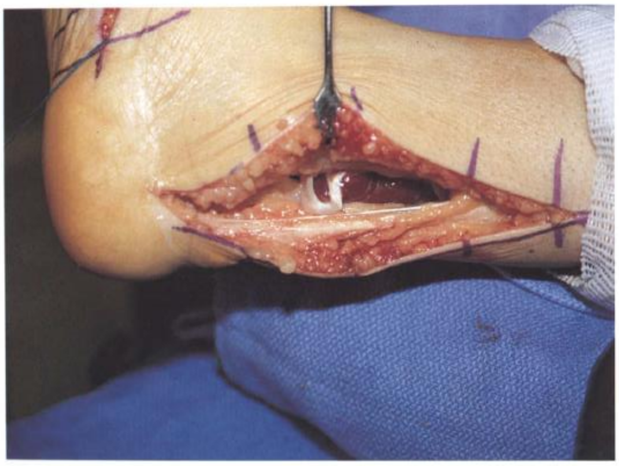


Figure 26 FHL is pulled from midfoot incision to posterior incision.

A transverse drill hole is made distal to the insertion of Achilles tendon and midway through the calcaneus. A vertical drill hole is also made deep to the insertion of Achilles to meet the transverse hole. FHL tendon is drawn through the drill hole (Figure 27).

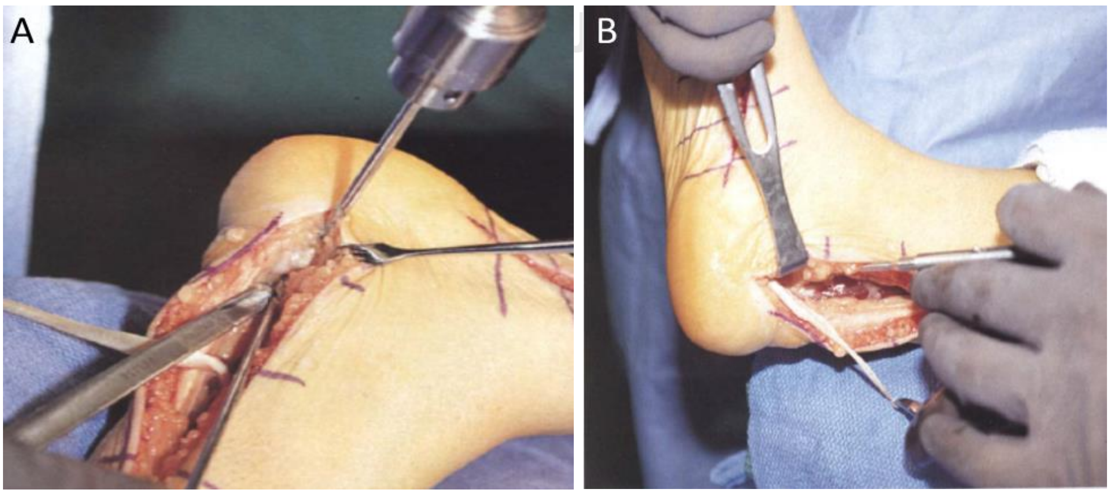


Figure 27 Two drill holes are made near the insertion of Achilles tendon (A) and FHL tendon is pulled through the tunnel B) [35].

FHL tendon is woven through Achilles tendon from distal to proximal (Figure 28). The tendon weaver is passed through Achilles tendon to make a tunnel in tendon. The tag suture on proximal part of FHL tendon is drew back through the tunnel to bring FHL tendon through Achilles tendon. This step is repeated to utilize the whole length of harvested tendon.

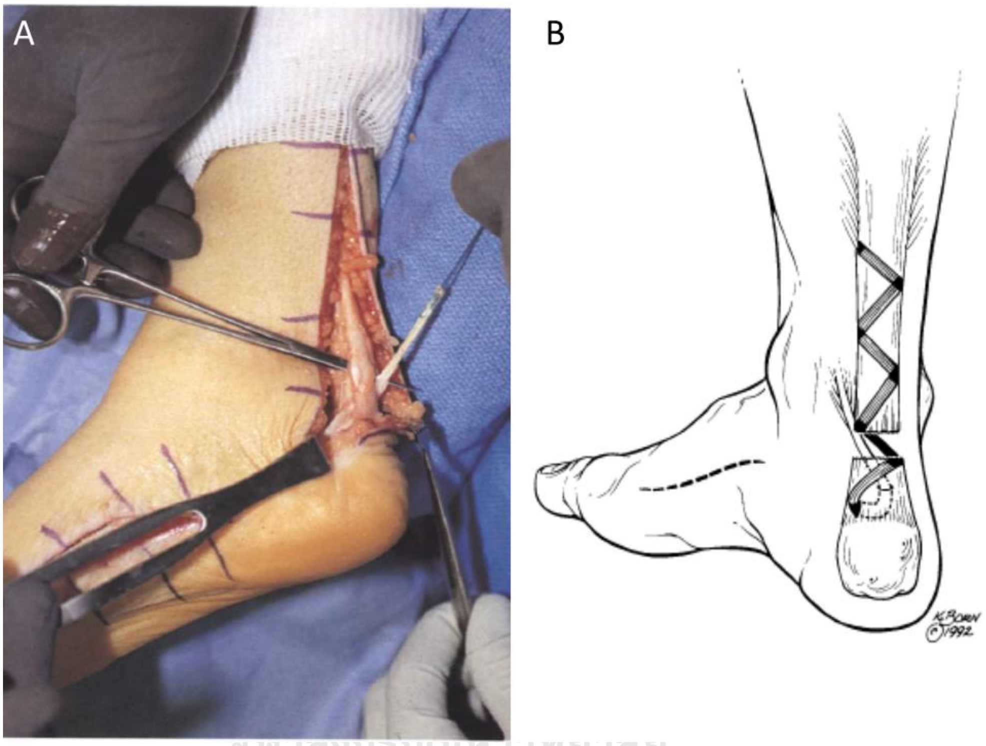


Figure 28 The drill holes are made near the insertion of Achilles tendon (A) and FHL tendon is pulled through the tunnel. (B) [35].

- Murphy technique (Minimally invasive technique) [6]

The direct posterior or posteromedial incision is made at the Achilles tendon to directly see and move Achilles tendon and FHL musculotendinous junction. A small incision, about 1.5 to 2 cm, is made on the plantar aspect of first metatarsophalangeal joint (Figure 29).

Figure 29 Forefoot incision for FHL harvesting [6]

To define the location for the incision, FHL tendon is palpated during great toe flexion and extension. FHL tendon is easily dissected while the toe is moved. The clamp is placed behind the tendon and the strong braided non absorbable suture is used to place a running whip stitch (Figure 30).

Figure 30 FHL tendon is carried into the incision with suture placed [6].

A scalpel is used to divide FHL tendon distally. A flexible hamstring tendon stripper is penetrated over the sutures and tendon. While the stripper is advanced over the tendon with the twisting motion, tension is applied to the sutures (Figure 31). At the level of MKH, the change in resistance is perceived. The FHL tendon is delivered through the proximal incision for reconstructive operations including pass through the drill holes at calcaneus, suture with the Achilles tendon, or the combination of both methods [6, 43].

Figure 31 Flexible tendon stripper is advanced over sutures [6].

Length of tendon graft

Previous researches reported that the length of harvested FHL tendon was different between techniques [12].

The posterior medial single incision approach is used to harvest the FHL within the tarsal tunnel. Although, this technique receives a shorter graft but it is long enough to insert the tendon on the calcaneus with a fit screw or with a suture technique. When the added tendon length is required, the double incision technique with the second incision at the medial aspect of foot near MKH is considered. The added 3 cm of tendon length is obtained from double incision technique if the FHL is cut at MKH [34]. For the longest tendon length, minimally invasive technique provides more tendon length than the previous two techniques [6].

The lengths of FHL tendon harvested through a single incision technique, double incision technique, and minimally invasive technique were reported in 2 cadaveric studies (Table 6). The length of the tendon was measured in situ. Different techniques of measurement and results were observed between studies.

Table 6 The length of harvested FHL tendon in cadaveric studies [12, 14, 36]

Authors	Year	Ethnic	n	Cadaveric type	Tendon length (cm) mean± SD (min-max)		
					Single incision technique	Double incision technique	Minimally invasive technique
Beger et al.[14]	2018	Turkish	20	Formalin fixed	5.75± 0.63 (4.52–6.86)	7.03± 0.86 (5.77–8.80)	20.22± 1.32 (16.82–21.97)
Mao et al.[12]	2015	Asian	64	Embalmed	5.08± 1.09 (3.32–10.35)	6.72± 1.02 (4.69–12.09)	17.49± 1.80 (13.51–20.52)
Tashjian et al.[36]	2003	US	14	Fresh frozen	5.16± 1.29 (3.4–6.9)	8.09± 1.63 (5.1–11.1)	-

Tashjian et al. (2013) measured the length between proximal tip of calcaneal tuberosity and the point of transection in the posterior incision to represent the average tendon graft from a single incision technique. Double incision technique was measured from the combination of the length of FHL proximal graft with the length of the distal remnant tendon in the midfoot incision (Figure 32) [36].

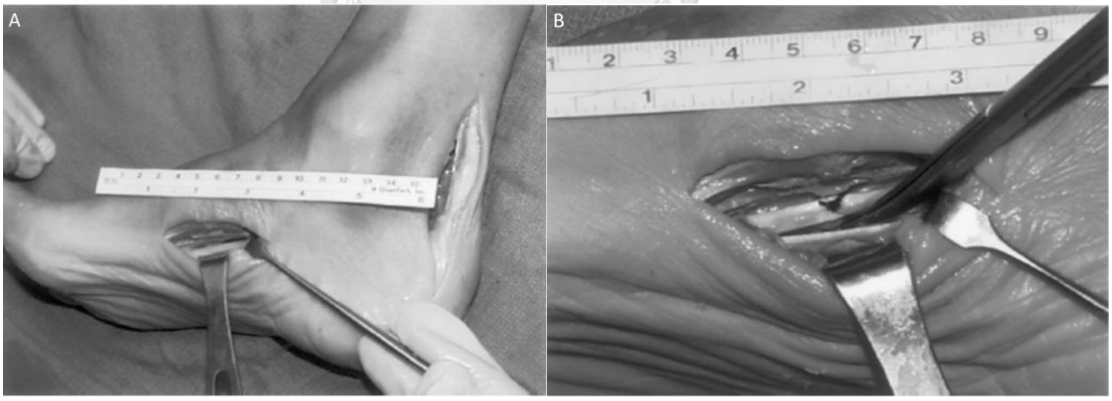


Figure 32 Double incision technique in the study of Tashjian et al. (A), FHL tendon at the level of MKH was sutured to represent the transection point in double incision technique (B) [36].

Mao et al. (2015) measured the distance from MTJ of FHL to sustentaculum tali, MKH, and first IP joint to represent the length of harvested tendon through the single posterior-medial incision, double incision, minimally invasive techniques respectively (Figure 33) [6].

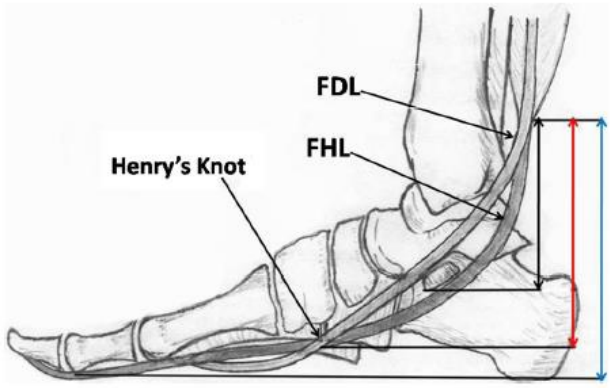


Figure 33 The landmarks of measuring the harvested tendon length in the study of Mao et al. (black line: single posterior-medial incision, red line: double incision, blue line: minimally invasive techniques) [12]

(FDL: flexor digitorum longus, FHL: flexor hallucis longus)

Complication

1. Although the results of FHL tendon transfer are good to excellent regardless the technique used for harvesting the tendon, complications are reported in some articles. The injuries of the distal branches of the posterior tibial nerve and artery were reported [12, 16]. According to Hansen technique, this single-incision technique has a small risk of nerve injury [15]. However, tibial neurovascular bundle resides medially and closely to FHL at the ankle. Thus, care should be taken to preserve this neurovascular bundle especially when distal transection is performed blindly [36, 42]. Moreover, the transection of tendon that performed distally to MKH in double incision technique may be the cause of MPN or LPN injury [12]. In the literature, they hypothesized that the difficult harvesting from the tendinous interconnection between FHL and FDL may be the cause of nerve injury. In one cadaveric study, injuries were observed in 33% of foot specimens including a complete rupture of MPN (25% of MPN and 8% of LPN). Moreover, a previous series using an approach

to MKH also reported an injury to MPN following FHL transfer for the re-rupture of Achilles tendon [44]. Although large percentage of nerve injury was observed in the cadaveric foot, the clinical symptom was described in a small number [41, 44]. Previous research suggested that nerve may be partially injured and not significant enough to cause the clinical symptoms. Furthermore, a long period of casting after surgery may prohibit the detection of symptoms. Since the surgical procedure is often performed in older patients and the symptoms are resemble polyneuropathy which can be coexisted in those patients [15].

2. Loss of FHL function after FHL tendon transfer for the treatment of chronic Achilles tendinosis or chronic Achilles tendon rupture was also reported [41]. Hahn et al. reported a loss of plantar flexion of the hallux while walking after Wapner technique of FHL tendon transfer. The pressures and forces under hallux are decreased and the load is transferred to the lateral metatarsal heads and lead to asymmetrical gait. They suggested that, these might be the compensatory effect after FHL tendon transfer [45]. Therefore, the authors recommended that a tenodesis of FHL tendon to FDL tendon should be performed with FHL transfer to preserve the function of hallux and avoided the cock-up deformity [12].

3. Some patients had the problem of hallux function associated to balance or problems with wearing sandals; despite of a mean reduction of passive range of motion of the first metatarsophalangeal joint to 20%. They hypothesized that these complications were related to aging and obesity [12, 46].

4. Other reported complications after FHL tendon transfer for chronic Achilles tendon rupture or tendinosis were deep-vein thrombosis, superficial infection or delayed wound-healing, risk of infection from large incision and painful scar [41, 47].

CHAPTER III

RESARCH METHODOLOGY

3.1 Target population and Sample population

This study was performed in the legs and feet of Thai soft and embalmed cadavers from Chula Soft Cadaver Surgical Training center, Faculty of Medicine, Chulalongkorn University.

Inclusion criteria

The cadaver is completely preserved and has no sign of previous surgery at the ankle and foot.

Exclusion criteria

The cadaver has deformity and obvious damage of the ankle and foot.

3.2 Sample size determination

Soft cadaver

According to the pilot study of ten feet from five soft cadavers, the result showed that the standard deviation of in situ FHL tendon length were 2.00, 1.12, and 1.17 cm in single incision, double incision and minimally invasive techniques respectively. These standard deviations were used to calculate for sample size of this descriptive study [48].

The confidence interval (CI) was set at 95%

$$n = Z^2_{\alpha/2}\,\sigma^2 / d^2$$

$Z_{\alpha/2} = Z_{0.05/2} = 1.96$ (two tail)

Single incision technique σ^2 = Variance of data = $(2.00)^2$

d = Acceptable error = 0.5 cm

$$n = Z^2_{\alpha/2}\,\sigma^2 / d^2$$

$$n = (3.84)(2.00)^2 / (0.5)^2$$

$n = (3.84)\,(4.00) / (0.25)$

$n = 61.44$

Double incision technique σ^2 = Variance of data = $(1.12)^2$

d = Acceptable error = 0.5 cm

$n = Z^2_{\alpha/2}\,\sigma^2 / d^2$

$n = (1.96)^2 (1.12)^2 / (0.5)^2$

$n = (3.84)\,(1.25) / (0.25)$

$n = 19.20$

Minimally invasive technique σ^2 = Variance of data = $(1.17)^2$

d = Acceptable error = 0.5 cm

$n = Z^2_{\alpha/2}\,\sigma^2 / d^2$

$n = (1.96)^2 (1.17)^2 / (0.5)^2$

$n = (3.84)\,(1.36) / (0.25)$

$n = 20.89$

The calculated sample sizes are at least 62 legs for single incision, 20 legs for double incisions, and 21 legs for minimal invasive techniques. Therefore, the sample size of soft cadaver in this study was 62 legs.

Embalmed cadaver

According to the pilot study, ten legs from five embalmed adult cadavers were examined. The result showed that the connection between FHL and FDL were type 1 (80%), type 5 (10%), and type 8 (10%). Type 2, 3, 4, 6, and 7 were not found. The proportion of type 1 is used to calculate for sample size of this study. The sample size estimation for embalmed cadaver was calculated by using the following formula [48].

The confidence interval (CI) was set at 95%.

$$n = Z^2_{\alpha/2} P (1-P) D / E^2$$

P = prevalence or proportion of event of interest for the study = 0.8

D = the design effect reflects the sampling design = 1 (for simple random sampling)

E = precision (or margin of error) = 10% of P

$$n = Z^2_{\alpha/2} P (1-P) D / E^2$$

$$n = (1.96)^2\ 0.8(1 - 0.8)(1) / (0.1 \times 0.8)^2$$

$$n = (1.96)^2\ 0.8(0.2)(1) / (0.1 \times 0.8)^2$$

$$n = (3.84)(0.16) / (0.0064)$$

$$n = 0.6144 / 0.0064$$

$$n = 96$$

The calculated sample size is at least 96 legs. Therefore, 96 embalmed cadaveric legs were included in this study.

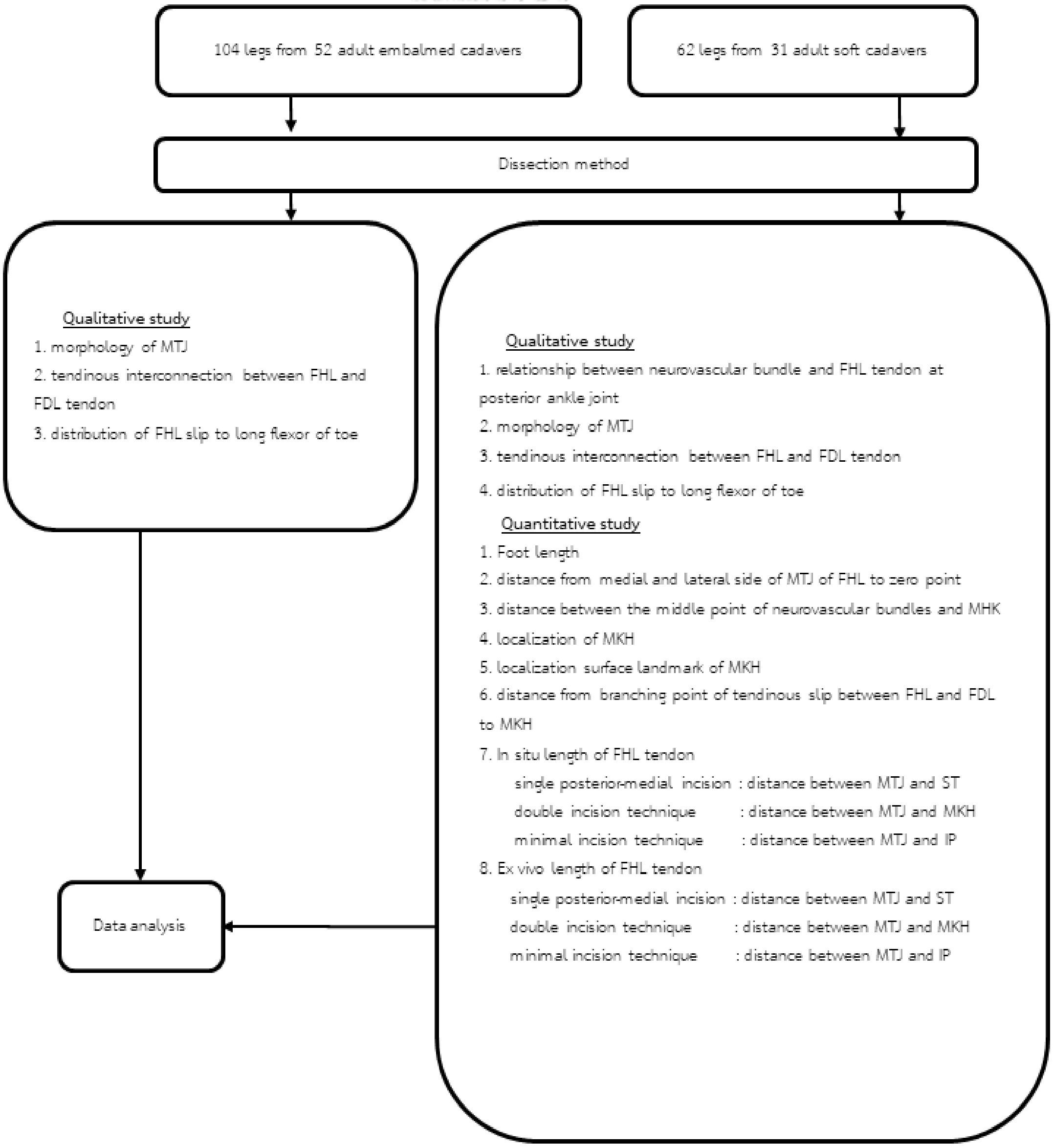
3.3 Tools

1. Materials for dissection consists of operating scissors, operating knife, surgical blade, forceps and probe
2. Machinist square and bandages (for adjust the ankle to neutral position)
3. Digital Vernier caliper (Mitutoyo ® 0-150 mm; range 150 mm, resolution 0.01 mm)

4. Measuring tape (Butterfly ® 0-150 cm; range 150 cm, resolution 1 mm)
5. Scale
6. Pins
7. Digital camera

3.4 Method

3.4.1 Research frame work



3.4.2 Measurement of foot length

The foot was aligned to neutral position by placed in machinist square and fixed with bandages. Foot length was measured from the most posterior portion of the calcaneus to the end of the longest toe [49] (Figure 34).

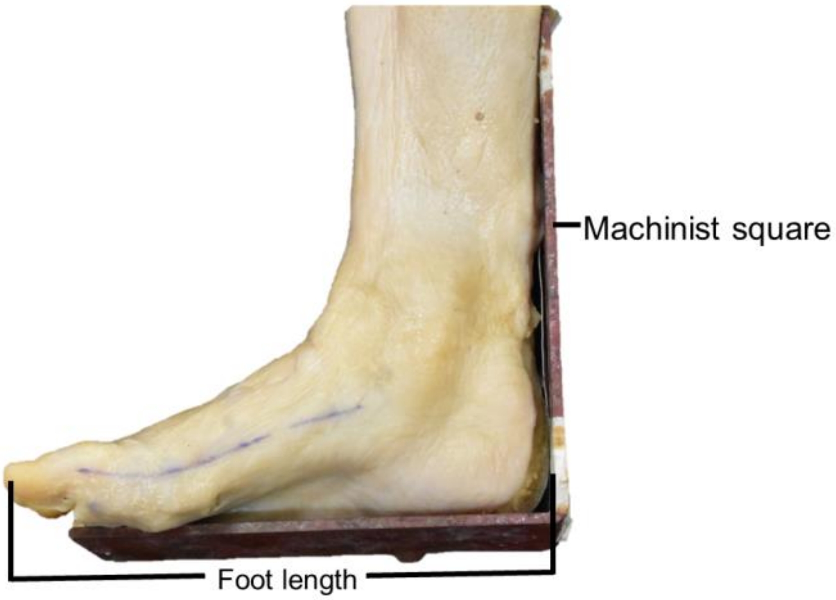


Figure 34 Alignment of foot was corrected with the machinist square. Foot length was measured from most posterior portion of the calcaneus to the end of the longest toe.

3.4.3 Cadaveric dissection

1. Surface marking

The medial end of plantar flexor crease at the base of the great toes (MC) and the most prominent point of navicular tuberosity (NT) were marked. The line joining between MC and NT was created for localization of MKH surface landmark (Figure 35).

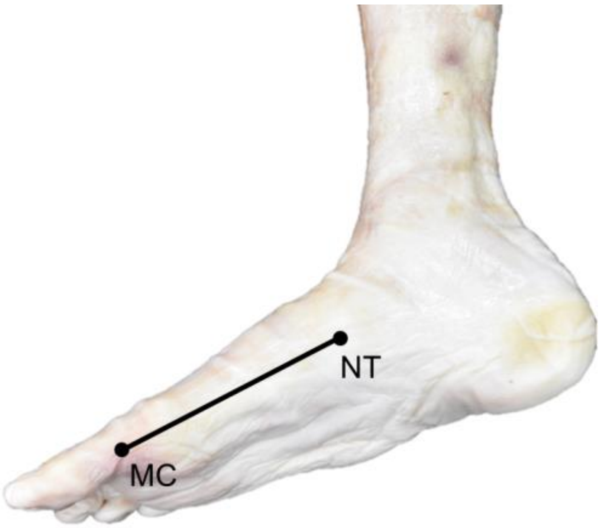


Figure 35 The line joining between MC and NT for localization of MKH surface landmark

(MC : medial end of plantar flexor crease at the base of the great toes, NT: navicular tuberosity)

2. Skin incision

The incision was performed in lower leg and planta as shown in figure 36. The skin, subcutaneous tissue, and fascia of medial side of lower leg, ankle and plantar surface of foot was turned over to each side.

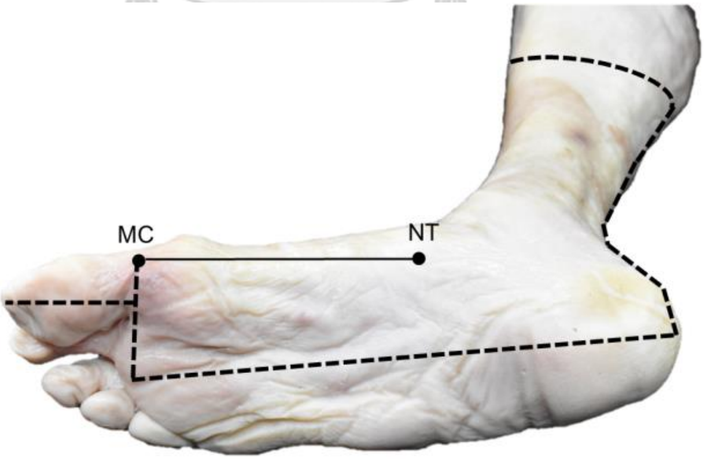


Figure 36 Photographs of right leg and plantar surface showing the skin incision line (dot line).

(MC : medial end of plantar flexor crease at the base of the great toes, NT: navicular tuberosity)

3.4.4 Structural identification

On the plantar surface of foot, plantar aponeurosis and medial plantar fascia was identified and cut to expose flexor digitorum brevis (FDB) and abductor hallucis muscle (ABH) (Figure 37). Normally, branches from medial plantar neurovascular bundle (MPNVB) locate between these two muscles. Main trunk of MPNVB was discovered by following these branches. Then, ABH and FDB were incised at their origin and turned up to expose MPNVB and lateral plantar neurovascular bundle (LPNVB) (Figure 38).

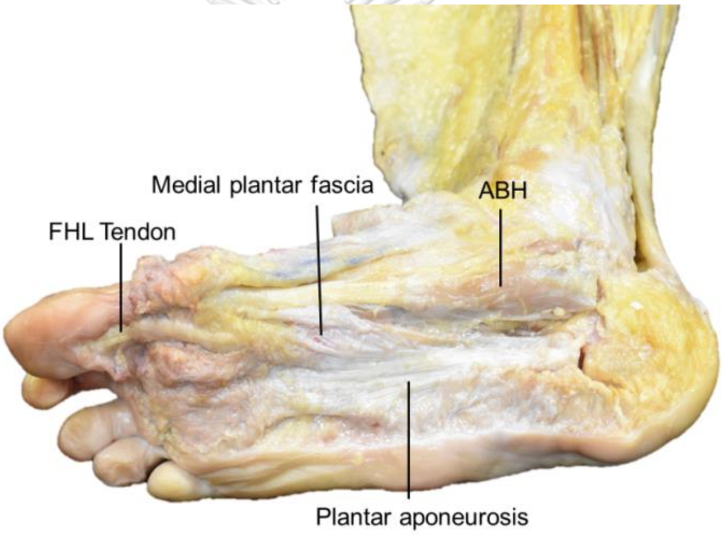


Figure 37 Photograph of plantar surface of right foot displaying the structure beneath skin and subcutaneous fatty tissue.

(ABH: abductor hallucis muscle, FHL: flexor hallucis longus)

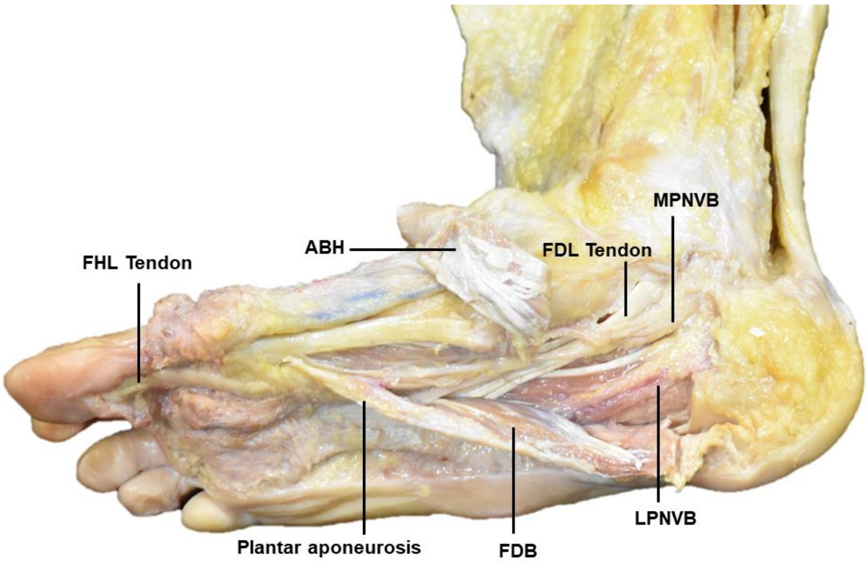


Figure 38 Photograph of right ankle and foot showing the anatomical structure under the layer of FDB and ABH.

(ABH: abductor hallucis muscle, FDL: flexor digitorum longus muscle, FHL: flexor hallucis longus muscle, LPNVB: lateral plantar neurovascular bundle, MPNVB: medial plantar neurovascular bundle)

FDB and ABH were separated to expose the tendon of FHL and FDL (Figure 39). MKH was identified as the crossing point of FDL and FHL tendon (Figure 40).

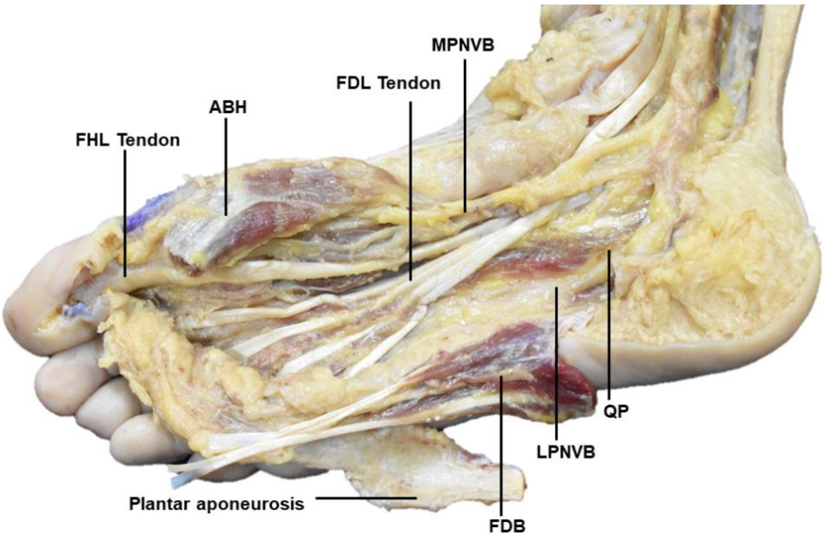


Figure 39 Photograph of right planta presenting the anatomical location of medial and lateral plantar neurovascular bundle, tendon of FDL and FHL.

(ABH: abductor hallucis muscle, FDL: flexor digitorum longus muscle, FHL: flexor hallucis longus muscle, LPNVB: lateral plantar neurovascular bundle, MPNVB: medial plantar neurovascular bundle, QP: quadratus plantae muscle)

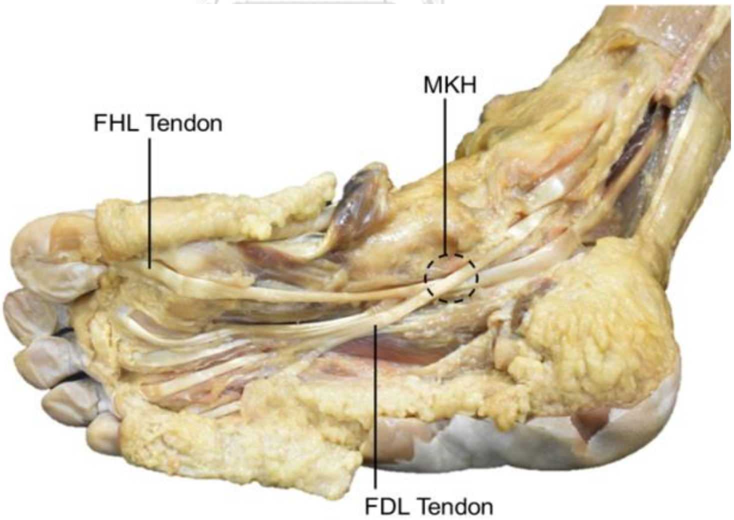


Figure 40 Photograph of right plantar surface of foot demonstrating Master knot of Henry or MKH which is the point where the tendon of FDL crossed the tendon of FHL.

(FDL: flexor digitorum longus muscle, FHL: flexor hallucis longus muscle, MKH: master knot of Henry)

At the medial side of ankle, flexor retinaculum which attach on medial malleolus and calcaneus was identified and cut at its posterior edge. The structures in tarsal tunnel from anterior to posterior including tendon of tibialis posterior, tendon of FDL, posterior tibial neurovascular bundle (TNVB), MTJ and tendon of FHL were identified (Figure 41-42).

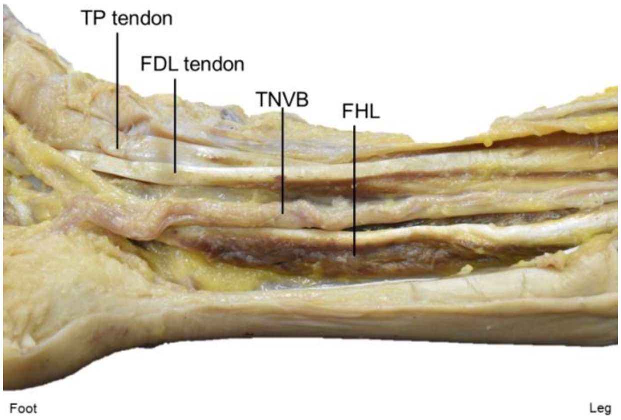


Figure 41 Right leg and ankle showing the contents in tarsal tunnel after flexor retinaculum and fascia sheet were removed.

(FDL: flexor digitorum longus muscle, FHL: flexor hallucis longus muscle, TNVB: tibial neurovascular bundle, TP: tibialis posterior muscle)

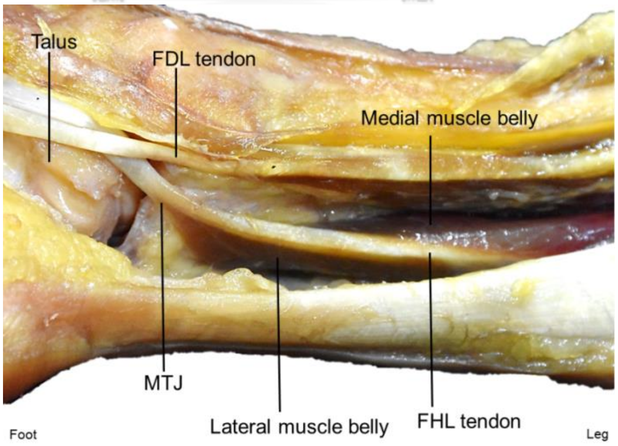


Figure 42 Musculotendinous junction (MTJ) of FHL in medial right leg

(FDL: flexor digitorum longus muscle, FHL: flexor hallucis longus muscle, MTJ: musculotendinous junction)

3.4.5 Observation and measurement

Soft cadavers

1. The relationship between neurovascular bundle and FHL at posterior ankle joint was evaluated and classified according to the study of Mao and coworkers into type I (no measurable distance) and type II (measurable distance) and the distance between them was be measured [23].
2. The morphology of MTJ was evaluated and classified according to the study of Mao and coworkers [23]. The distance from medial and lateral side of MTJ of FHL to zero point, which is intersection between distal osseous part of tibia and FHL tendon, was measured (Figure 43).

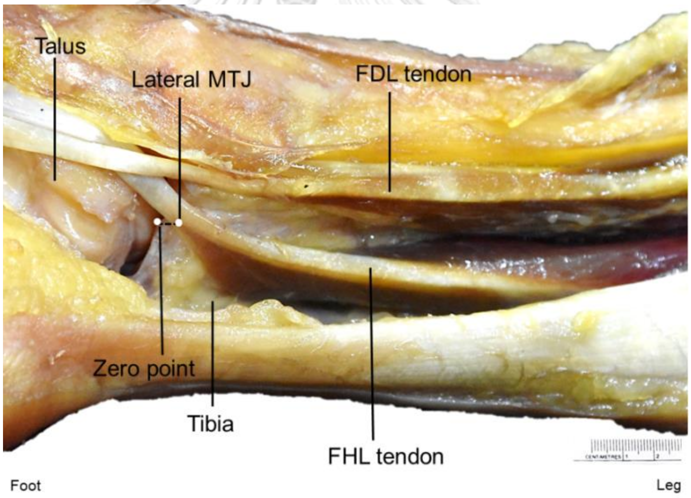


Figure 43 The distance from lateral MTJ of FHL to zero point

(FDL: flexor digitorum longus muscle, FHL: flexor hallucis longus muscle, MTJ: musculotendinous junction)

3. The distance between the middle point of neurovascular bundle at plantar surface of foot (MPNVB and LPNVB) and the middle point of MKH was record (Figure 44).

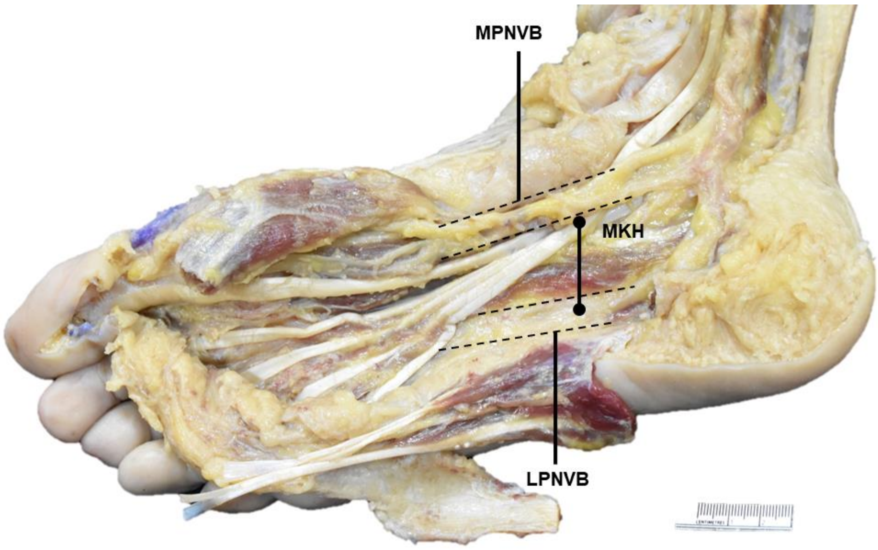


Figure 44 The distance between MKH and the middle point of lateral plantar neurovascular bundle

(LPNVB: lateral plantar neurovascular bundle, MKH: master knot of Henry, MPNVB: medial plantar neurovascular bundle)

4. To localize the MKH, the distances from MKH to the most prominent point of medial malleolus (MM), navicular tuberosity (NT) and the middle point of first interphalangeal joint (IP) were recorded (Figure 45).

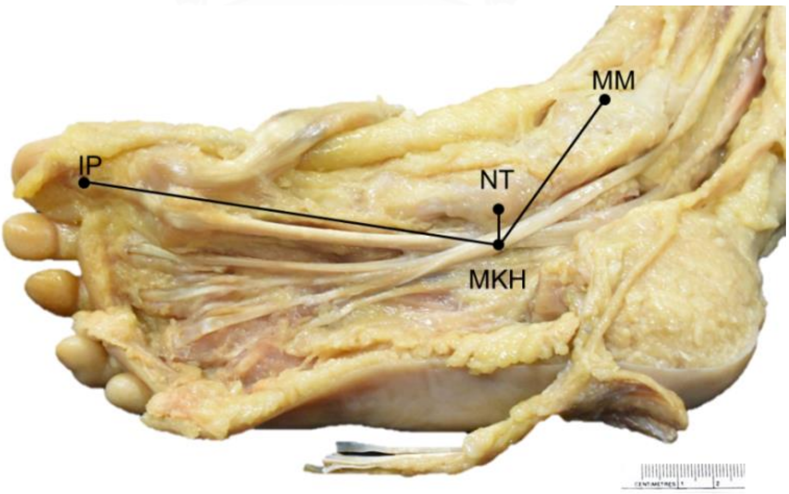


Figure 45 The distance from MKH to the most prominent point of medial malleolus (MM), navicular tuberosity (NT) and first interphalangeal joint (IP)

5. The surface location of MKH was localized by measuring the distance from MC to NT (MC-NT). If the location of MKH is not perpendicular to NT on MC-NT line, point “A” was defined. A is the perpendicular point of MKH on MC-NT line. The distances between MC and A, MKH and A were also measured (Figure 46).

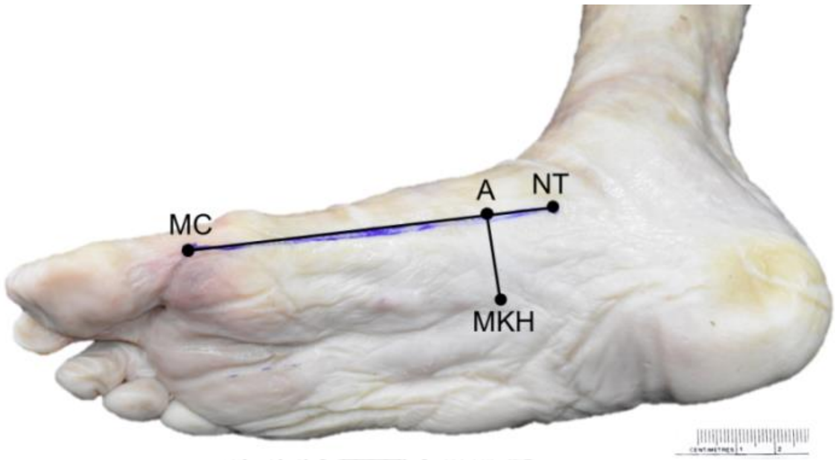


Figure 46 Surface distance from MC to NT (MC-NT), MC to A and MKH to A

(MC: medial end of plantar flexor crease, MKH: master knot of Henry, NT: navicular tuberosity)

6. The tendinous interconnection between the FHL and FDL tendons was identified and classified according to the study of Beger et al. (Figure 15) [(14)]. The distance from branching point of tendinous interconnection to MKH was measured (Figure 47).

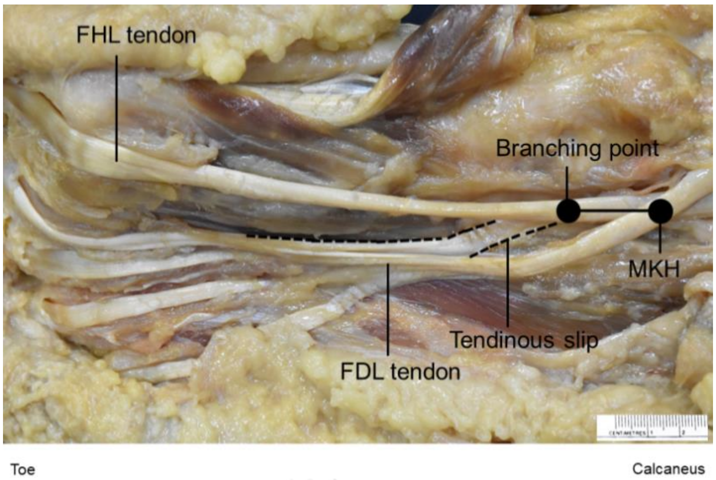


Figure 47 Localization of tendinous slip between FHL and FDL by measuring the distance from branching point of tendinous interconnection to MKH

(FDL: flexor digitorum longus muscle, FHL: flexor hallucis longus muscle, MKH: master knot of Henry)

7. The distribution of FHL slip to the long flexor tendon of toes was examined by manually applied the tension to each toe of the foot. The movement of FDL and FHL tendons while moving each toe was recorded.
8. To study in situ length of FHL tendon in single incision, double incision and minimally invasive techniques, sustentaculum tali (ST), MKH and first interphalangeal joint (IP) were marked according to the study of Mao et al. (Figure 48) [16].
   - The distance between MTJ of FHL and ST was represented the length of the FHL tendon for harvesting through a single posterior-medial incision.
   - The distance between MTJ of FHL and MKH was measured to show the available FHL graft from double-incision technique.
   - In accordance with the minimally invasive technique, the length from MTJ of the FHL to the first IP joint was measured.

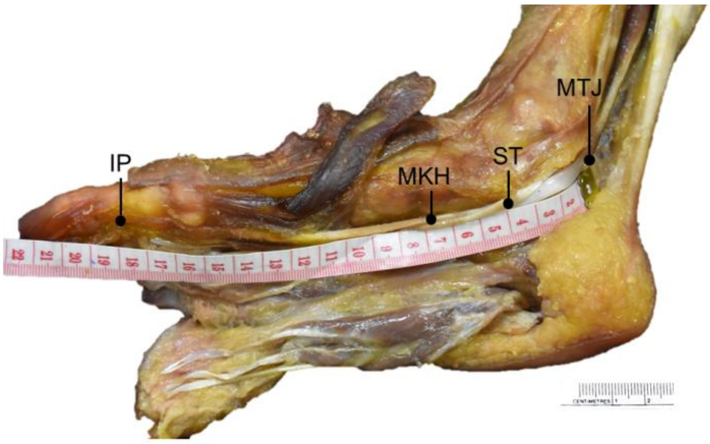


Figure 48 The distances between MTJ of FHL and IP, MKH, ST

(MTJ: musculotendinous junction, IP: first interphalangeal joint, MKH: master knot of Henry, ST: sustentaculum tali)

9. To identify the ex vivo length of FHL tendon, the points which represent the location of ST, MKH and IP were marked on FHL tendon. After that, FHL tendon was cut at the insertion. Ex vivo length of FHL tendon was measured from MTJ to three marked points on FHL tendon (Figure 49).

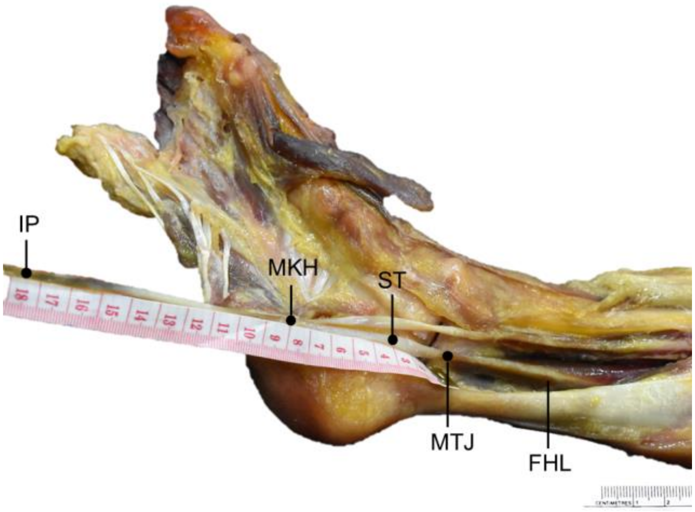


Figure 49 The distances from MTJ and the marked point on FHL tendon (IP, MKH, ST)

(MTJ: musculotendinous junction, IP: first interphalangeal joint, MKH: master knot of Henry, ST: sustentaculum tali)

10. After all observation and measurement, the leg and foot were photographed. Lastly, FHL and FDL were cut and removed from cadavers

for reanalyzing type of tendinous interconnection and measuring the width of tendinous interconnection at branching point (Figure 50).

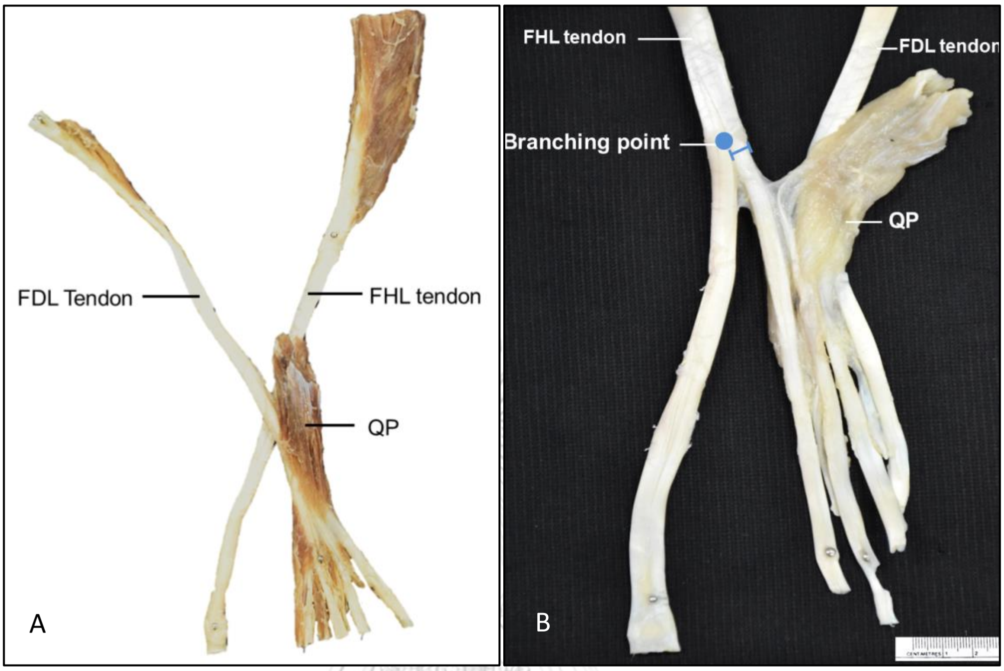


Figure 50 FHL and FDL after cut and removed from cadavers for re-analyzation (A) The width of tendinous slip at branching point (B)

(FDL: flexor digitorum longus muscle, FHL: flexor hallucis longus muscle, QP: quadratus plantae)

All distances and parameters were measured twice with the same digital Vernier caliper or measuring tape by same researcher. Importantly, the ankle joint was set in neutral position during measurement.

Embalmed cadavers

1. The morphology of MTJ was evaluated and classified according to the study of Mao and coworkers [23].
2. The tendinous interconnection between the FHL and FDL tendons was identified and classified according to the study of Beger et al.[14].
3. The distribution of FHL slip to long flexor tendon of toes was examined by manually applied the tension to each toe of the foot. The movement of FDL and FHL tendons while moving each toe was recorded.

3.5 Data collection

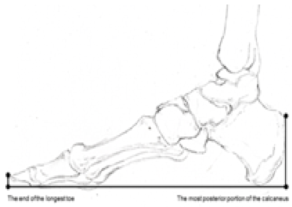
All data was recorded in case record form.

Case Record Form (Soft cadaver)

Faculty of Medicine, Chulalongkorn University

No. ____ Sex: ☐ Male ☐ Female Side: ☐ Left ☐ Right Code. ______ Age: _____ years W:_____kg H:______ cm

1. Foot length

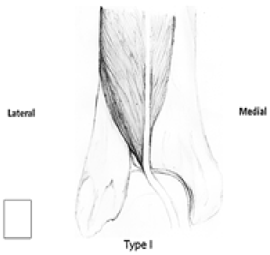


The most posterior portion of the calcaneus to the end of the longest toe) : 1. ....cm

2. ....cm

2. Flexor hallucis longus (FHL)

2.1 Morphology of FHL

☐


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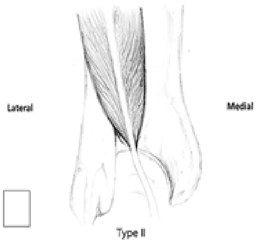

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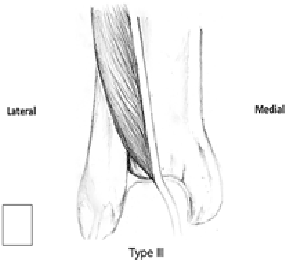

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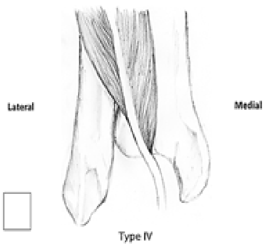


☐


2.2 Distance from MTJ to zero point

☐ Medial belly Distance to Zero point: I).......................mm II)..............................mm

☐ Lateral belly Distance to Zero point: I).......................mm II)..............................mm

2.3 Relationship between neurovascular bundle structure and FHL muscle at posterior ankle joint

☐ Type I Distance: I)........................mm II)...............................mm

☐ Type II No distance

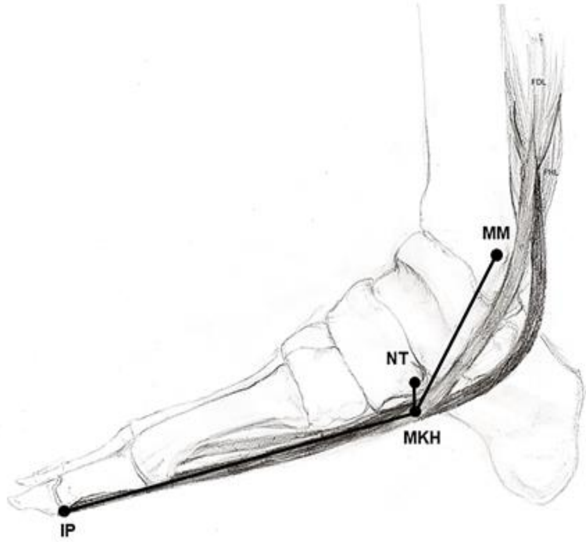
3. Master knot of Henry (MKH)

3.1 Relationship between neurovascular bundle structure and MKH

Structures	I (mm)	II (mm)
1. Medial plantar nerve and vessels		
1. Lateral plantar nerve and vessels		

3.2 Localization of MKH

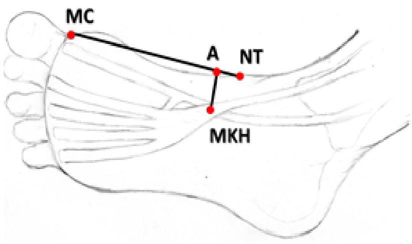
3.2.1 Location of MKH

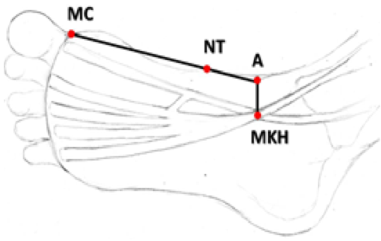


Distances	I (mm)	II (mm)
1. MKH to First IPJ (IP)		
1. MKH to Navicular tuberosity (NT)		
1. MKH to Medial malleolous (MM)		

MKH: master knot of Henry, MM: medial malleous, NT: navicular tuberosity IP: proximal interphalangeal joint of great toe

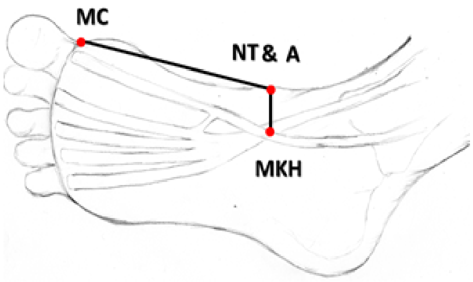
3.2.2 Surface landmark of MKH





Location of A ☐ Anterior to NT ☐ Posterior to NT

Distances	I (mm)	II (mm)
1. MC-NT		
1. MC-A		
1. NT-A		
1. A-MKH		

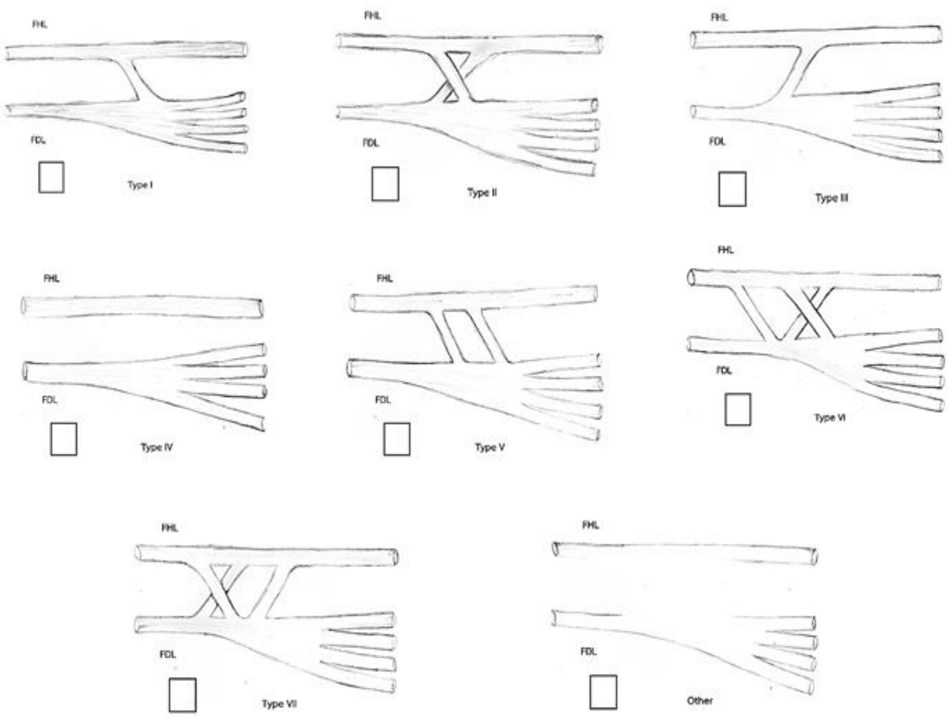


Location of A ☐ At NT

Distances	I (mm)	II (mm)
1. MC-NT &A		
1. NT&A-MKH		

4. Connection between FHL and FDL

4.1. Classification of tendinous interconnection between FHL and FDL



4.2. Localization of tendinous interconnection between FHL and FDL

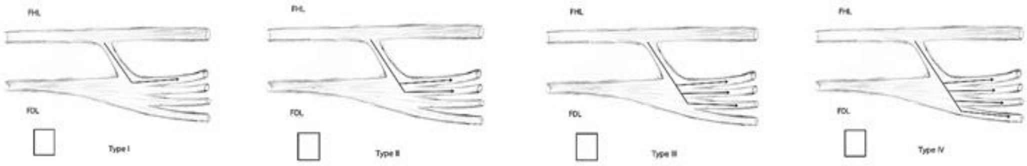
Proximal end of tendinous slip from FHL

☐ Proximal slip Distance to MKH : I)......................mm II)..............................mm

☐ Middle slip Distance to MKH : I)......................mm II)..............................mm

☐ Distal slip Distance to MKH : I)......................mm II)..............................mm

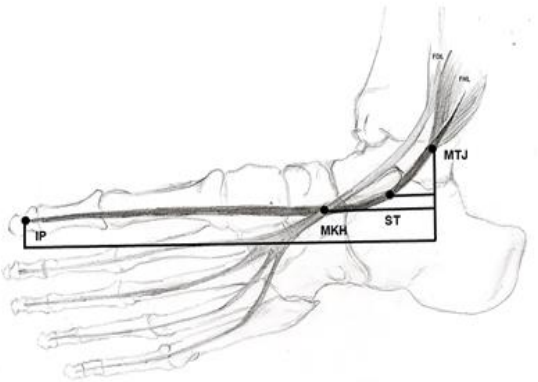
4.3 Contribution of FHL slips to long flexor tendon of toes



Pulled tendon	Toes				
	I	II	III	IV	V
1. FHL					
1. FDL					

5. Length of FHL tendon from musculotendinous junction (MTJ)

5. 1 In situ length of FHL tendon



MKH: master knot of Henry, MTJ: musculotendinous junction of FHL, IP: proximal interphalangeal joint of great toe ST: sustentaculum tali

Distances	I (mm)	II (mm)
1. MTJ to IP		
1. MTJ to MKH		
1. MTJ to ST		

5. 2 Ex vivo length of FHL tendon

Distances	I (mm)	II (mm)
1. MTJ to IP		
1. MTJ to MKH		
1. MTJ to ST		

Case Record Form (Embalmed cadaver)

Faculty of Medicine, Chulalongkorn University

Table No. ______________ Sex: ☐ Male ☐ Female Cadaveric Code. ______________ Age: _________ years

1. Flexor hallucis longus (FHL)

Morphology of FHL

Type I

☐ L ☐ R

Type II

☐ L ☐ R

Type III

☐ L ☐ R

Type IV

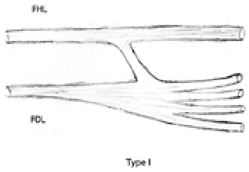
☐ L ☐ R

Other

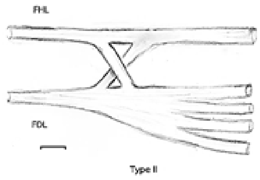
☐ L ☐ R

2. Connection between FHL and FDL

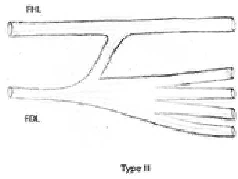
Classification of tendinous interconnection between FHL and FDL



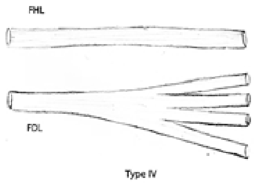
☐ L ☐ R



☐ L ☐ R



☐ L ☐ R



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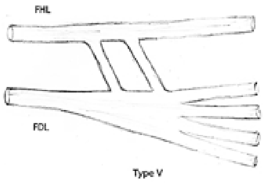
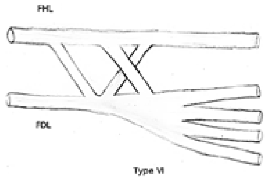


☐ L ☐ R



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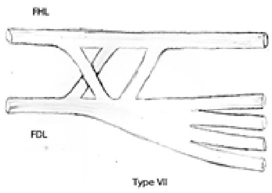
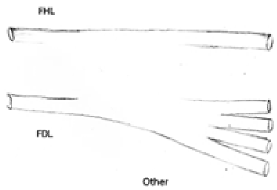
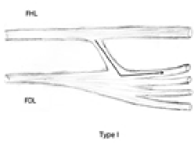


☐ L ☐ R

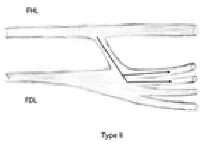


☐ L ☐ R

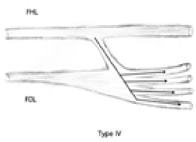
3. Contribution of FHL slips to long flexor tendon of toes



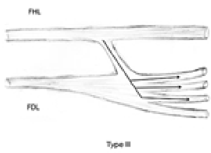
☐ L ☐ R



☐ L ☐ R



☐ L ☐ R



☐ L ☐ R

Pulled tendon	Movement of toes									
	I		II		III		IV		V	
	L	R	L	R	L	R	L	R	L	R
1. FHL										
1. FDL										

3.6 Data analysis

The statistical analysis was performed by SPSS software version 22.0. Type of MTJ, tendinous interconnection between FHL and FDL tendon, and contribution of tendinous slip to long flexor tendon of toes was statistically analyzed as percentage and prevalence.

The assumption of the data distribution was evaluated to classify the equality of the variances (normal/ abnormal distribution). All data from measurement was statistically analyzed to demonstrate minimum, maximum, mean and SD. To compare between genders, unpaired t-test (for parametric test) or Mann-Whitney U test (for nonparametric test) was used. The difference between left and right side was examined with paired t-test (for parametric test) or Wilcoxon signed-rank test (for nonparametric test). The difference between in situ and ex vivo tendon length was analyzed with paired t-test or Wilcoxon signed-rank test as well. A *p*-value of less than 0.05 was considered to be statistically significant.

The statistical analysis for assessing the associative relationship between the foot length and the tendon length, and between the width and the distribution of tendinous interconnection was the Pearson correlation test.

CHAPTER IV

RESULTS

One hundred and sixty six legs from eighty three cadavers (52 embalmed and 31 soft cadavers) were analyzed in this study. Forty two of them were male and forty one of them were female. The demographic information of cadavers was displayed in table 7.

Table 7 Demographic data of specimens in this study

Gender **n (%)** • Male • Female	 42 (50.6) 41 (49.4)
Age mean±SD (min-max) year	78.69±12.63 (32-100)
Height mean±SD (min-max) cm	161.19±7.82 (150-178)
Weight mean±SD (min-max) kg	57.68±7.04 (50-75)

4.1 Foot length

The results and analysis of the foot length from 31 soft cadavers are illustrated in term of mean±SD, minimum and maximum in Table 8. The mean length of foot in male and female was 24.65±1.20 and 22.46±1.16 cm, respectively. Statistically significant differences were found between genders in both sides and between sides in female.

Table 8 The mean foot length divided by genders and sides

Gender/Side	Foot length (cm) mean ± SD (min-max)			Difference between sides
	Left	Right	Total	
Male	(n=9) 24.64±1.22 (22.5-26.8)	(n=9) 24.66±1.25 (22.8-27.0)	(n=18) 24.65±1.2 0 (22.5-27.0)	*p*-value = 0.937
Female	(n=22) 22.38±1.22 (20.0-25.0)	(n=22) 22.55±1.13 (20.3-24.8)	(n=44) 22.46±1.16 (20.0-25.0)	*p*-value = 0.026
Total	(n=31) 23.03±1.59 (20.0-26.8)	(n=31) 23.16±1.50 (20.3-23.16)	(n=62) 23.10±1.53 (20.0-27.0)	-
Difference between genders	*p*-value = 0.00	*p*-value = 0.00	-	

4.2 MTJ morphology

MTJ morphology was examined in both soft and embalmed cadavers. Two morphological types of MTJ were identified in 166 legs including type 1 and type 3 (Figure 51-54) with a prevalence of 145 (87.35%) and 21 (12.65%) of cases respectively (Table 9). Symmetrical type of MTJ morphology, in which left and right sides had the same type of morphology, was found in 74 (89.16%) of cases (Table 10).

Table 9 Prevalence of MTJ morphology

Type of MTJ morphology	n (%)						
	Male			Female			Total (n=166)
	Left (n=42)	Right (n=42)	Total (n=84)	Left (n=41)	Right (n=41)	Total (n=82)	
1	35 (21.08)	32 (19.28)	67 (40.36)	39 (23.49)	39 (23.49)	78 (46.99)	145 (87.35)
2	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
3	7 (4.22)	10 (6.02)	17 (10.24)	2 (1.20)	2 (1.20)	4 (2.41)	21 (12.65)
4	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

(MTJ: musculotendinous junction)

Table 10 Prevalence of symmetrical type of MTJ morphology

	n (%)		
	Male	Female	Total
Symmetry			
1	30 (36.15)	38 (45.78)	68 (81.93)
3	5 (6.02)	1 (1.21)	6 (7.23)
total	35 (42.17)	39 (46.99)	74 (89.16)
Asymmetry			
1&3	7 (8.43)	2 (2.41)	9 (10.84
Total	42 (50.60)	41(49.40)	83 (100.00)

(MTJ: musculotendinous junction)

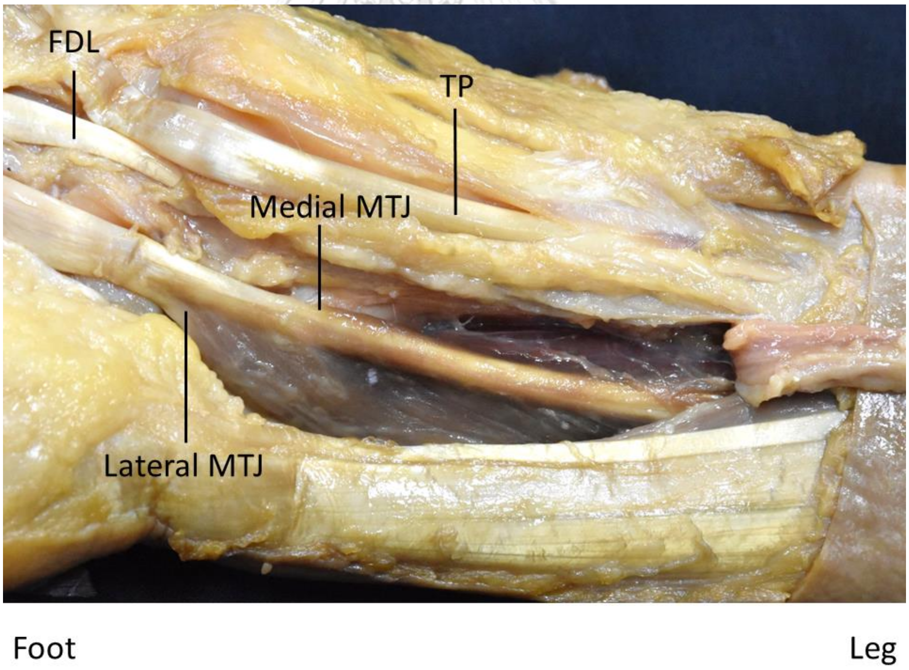


Figure 51 Photograph of type 1 MTJ morphology of right leg, the lateral muscle belly reached more distally than medial muscle belly.

(FDL: flexor digitorum longus, MTJ: musculotendinous junction, TP: tibialis posterior)

Figure 52 Photograph of type 1 MTJ morphology showing a longer lateral belly

(MTJ: musculotendinous junction)

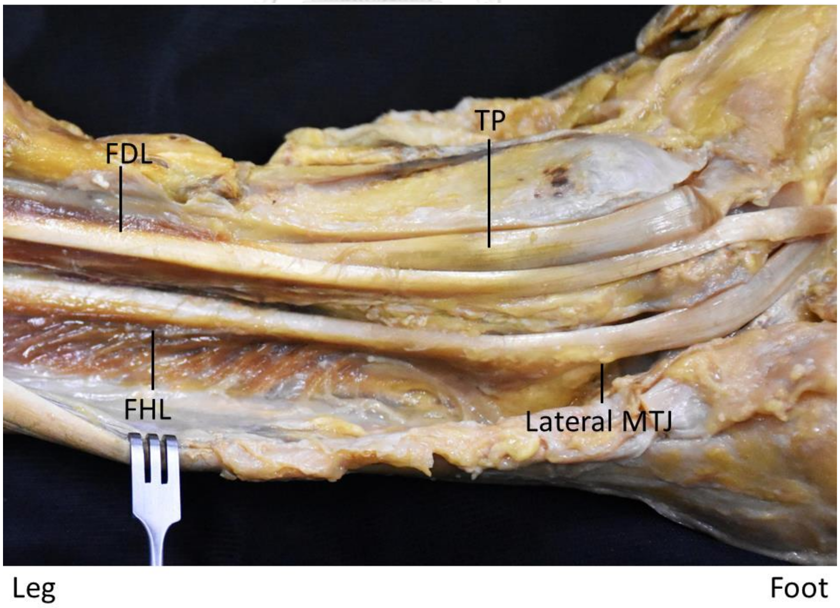


Figure 53 Photograph of type 3 MTJ morphology of left leg with only lateral muscle belly.

(FDL: flexor digitorum longus, FHL: flexor hallucis longus, MTJ: musculotendinous junction, TP: tibialis posterior)

Figure 54 Photograph of type 3 MTJ morphology showing only lateral muscle belly (MTJ: musculotendinous junction)

4.3 MTJ location

MTJ location was determined only in 62 legs of soft cadavers by measuring the distance from medial and lateral MTJs to the zero point. The results are shown in table 11-12. Only lateral muscle belly reached distal to the zero point (41 cases, 66.13%) with a mean distance of 5.83±11.64 mm. In contrast, the medial muscle belly reached proximal to the zero point with a mean distance of -21.99±13.21 mm. No statistically significant difference was found between genders and sides.

Table 11 Prevalence of FHL muscle belly which located distal to zero point

Low lying of FHL	n (%)						
	Male			Female			Total (n=62)
	Left (n=9)	Right (n=9)	Total (n=18)	Left (n=22)	Right (n=22)	Total (n=44)	
Lateral muscle belly	7 (11.29)	7 (11.29)	14 (22.58)	13 (20.97)	14 (22.58)	27 (43.55)	41 (66.13)
Medial muscle belly	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Both muscle bellies	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
No	2 (3.23)	2 (3.23)	4 (6.45)	9 (14.52)	8 (12.90)	17 (27.42)	21 (33.87)

(FHL: flexor hallucis longus)

Table 12 Mean distance from medial and lateral MTJ to zero point

Muscle belly	Distance (mm) mean± SD (min-max)								
	Male				Female				Total (n=62)
	Left (n=9)	Right (n=9)	Total (n=18)	Difference between sides	Left (n=22)	Right (n=22)	Total (n=44)	Difference between sides	
Lateral belly	8.59±9.60 (-6.54 – 20.88)	8.95±10.24 (-8.39 – 21.21)	8.77±9.63 (-8.39 – 21.21)	*p*-value = 0.804	3.86±11.77 (-18.27 – 20.96)	5.40±12.97 (-30.62 – 5.54)	4.63±12.26 (-30.62 – 20.96)	*p*-value = 0.322	5.83±11.64 (-30.62 – 21.21)
Difference between genders -Left -Right	*p*-value = 0.260 *p*-value = 0.514								
Medial belly	-27.19±11.32 (-42.12 – -12.78)	-21.57±6.46 (-28.13 – -12.08)	-24.79±9.66 (-42.12 – -12.78)	*p*-value = 0.690	-22.34±13.84 (-51.02 – -4.93)	-19.76±14.70 (-65.95 – -5.54)	-21.08±14.16 (-65.95 – -4.93)	*p*-value = 0.394	-21.99±13.21 (-65.95 – -4.93)
Difference between genders -Left -Right	*p*-value = 0.383 *p*-value = 0.243								

+: distal to zero point -: proximal to zero point

(MTJ: musculotendinous junction)

4.4 Relationship between neurovascular bundle and FHL at the ankle joint

In all specimens of this study, the distance between neurovascular bundle and FHL at ankle was not appearing or type I according to the study of Mao and coworkers (Figure 55) [23].

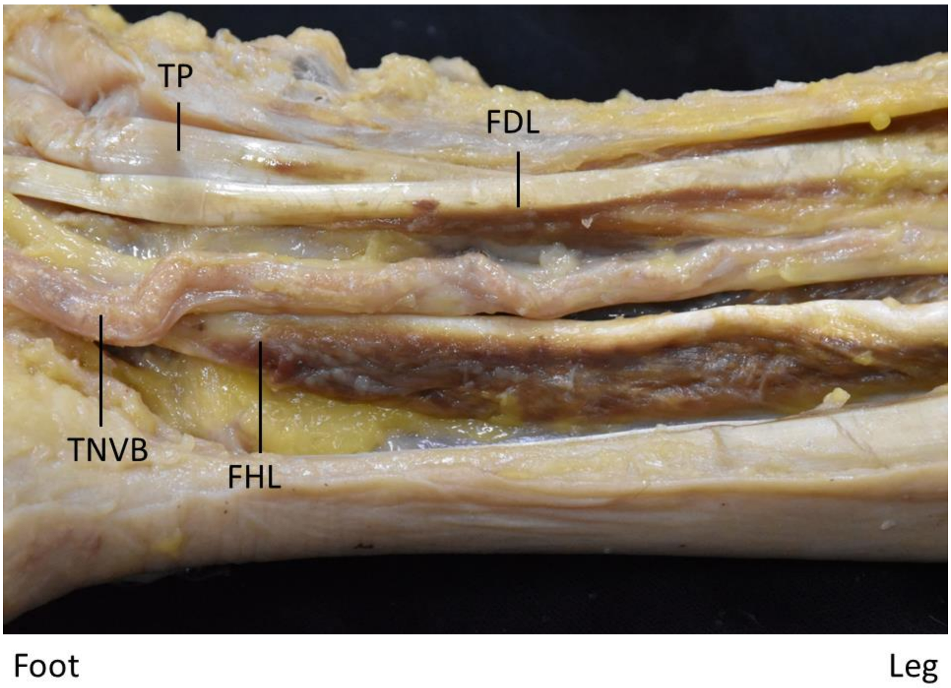


Figure 55 Photograph of medial side of right ankle demonstrated the closely relationship between tibial neurovascular bundle (TNVB) and FHL

(FDL: flexor digitorum longus, FHL: flexor hallucis longus, TNVB: tibial neurovascular bundle , TP: tibialis posterior)

4.5 Location of MKH

The results and analysis of MKH location is displayed in table 13. The location of MKH was identified at 117.11±1.00 mm proximal to IP, 26.28±4.75 mm under NT and 59.58±7.51 mm distal to MM (Figure 56). A statistically significant difference between genders was observed in MKH–IP of left and right sides (p =0.002, 0.004 respectively) and MKH-NT of right side (p = 0.048).

Table 13 Distances from MKH to IP, NT and MM

Anatomical landmark	Distance (mm) mean ± SD (min-max)								
	Male				Female				Total (n=62)
	Left (n=9)	Right (n=9)	Total (n=18)	Difference between sides	Left (n=22)	Right (n=22)	Total (n=44)	Difference between sides	
IP	124.69±9.04 (106.56 – 137.88)	126.39±12.39 (110.24 – 151.27)	125.54±10.55 (106.56 – 151.27)	*p*-value = 0.623	113.30±8.11 (93.14 – 129.50)	114.03±6.95 (100.27 – 128.20)	113.66±7.47 (93.14 – 129.50)	*p*-value = 0.628	117.11±1.00 (93.14 – 151.27)
Difference between genders - Left - Right	*p*-value = 0.002 *p*-value = 0.004								
NT	29.45±7.06 (21.38 – 40.91)	27.88±4.15 (19.53 – 33.16)	28.67±5.68 (19.53 – 40.91)	*p*-value = 0.495	26.21±3.51 (17.93 – 33.73)	24.40±4.32 (18.30 – 35.87)	25.31±3.99 (17.93 – 35.87)	*p*-value = 0.134	26.28±4.75 (17.93 – 40.91)
Difference between genders - Left - Right	*p*-value = 0.220 *p*-value = 0.048								
MM	63.32±9.80 (47.02 – 78.71)	60.02±11.02 (34.59 – 75.27)	61.67±10.26 (34.59 – 78.71)	*p*-value = 0.497	60.36±6.49 (48.91 – 78.07)	57.10±5.06 (44.43 – 67.05)	58.72±5.98 (44.43 –78.07)	*p*-value = 0.062	59.58±7.51 (34.59 –78.71)
Difference between genders - Left - Right	*p*-value = 0.338 *p*-value = 0.315								

(IP: first interphalangeal joint, NT: navicular tuberosity, MM: medial malleolus)

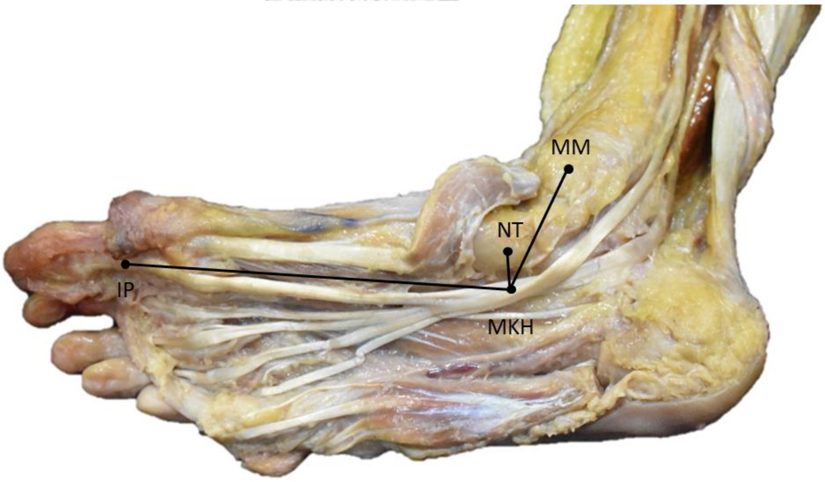


Figure 56 Plantar surface of right foot showing the distance from MKH to the first interphalangeal joint (IP), navicular tuberosity (NT) and medial malleolus (MM).

(MKH: master knot of Henry, MM: medial malleolus , NT: navicular tuberosity)

4.6 Surface landmark of MKH

The result and analysis of MKH surface landmark is shown in table 14-15. Point A on MC-NT line could be resided anterior to NT (66.1 %), at NT (27.4%) and posterior to NT (6.5%) (Table 14, Figure 57-59). The mean length of MC-NT and MC-A line were 107.36±8.60 and 101.72±12.01 mm, respectively. The mean perpendicular length from MKH to A (MKH-A) was 25.11+5.37 mm. In MC-NT length of female, a statistically significant difference between sides was found (p = 0.006). Moreover, the statistically significant difference between genders was present in MC-NT on left and right sides (p = 0.005, 0.034) and MC-A and MKH-A on right side (p = 0.024. 0.015).

Table 14 Incidence of location of MKH on MC-NT line (A)

Location of MKH	n (%)						Total (n=62)
	Male			Female			
	Left (n=9)	Right (n=9)	Total (n=18)	Left (n=22)	Right (n=22)	Total (n=44)	
At NT	4 (44.4)	3 (33.3)	7 (38.9)	4 (18.2)	6 (27.3)	10 (22.7)	17 (27.4)
Anterior to NT	3 (33.33)	5 (55.6)	8 (44.4)	17 (77.3)	16 (72.7)	33 (75.0)	41 (66.1)
Posterior to NT	2 (22.22)	1 (11.1)	3 (16.7)	1 (4.5)	0 (0)	1 (2.3)	4 (6.5)

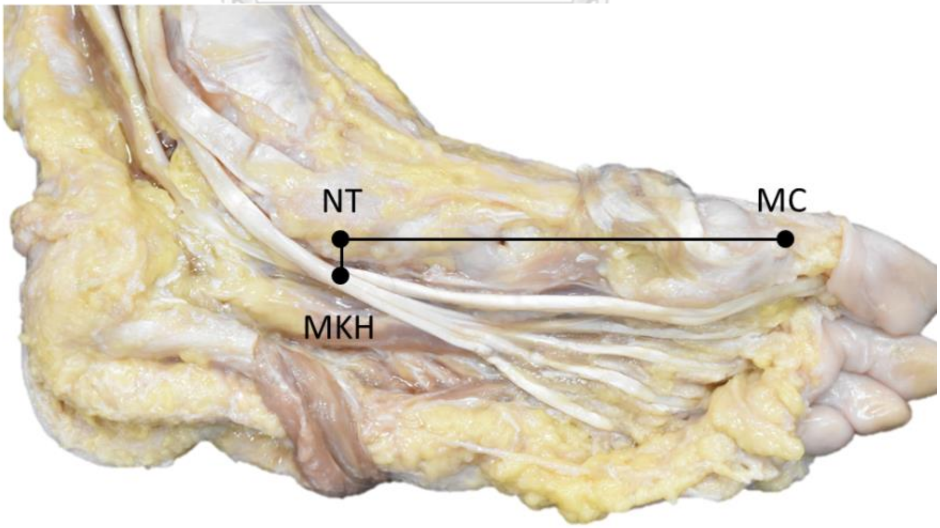


Figure 57 Photograph of left foot demonstrated the location of point A resided at NT on MC-NT line.

(MC: medial end of plantar flexion crease at the base of the great toe, MKH: master knot of Henry, NT: navicular tuberosity)

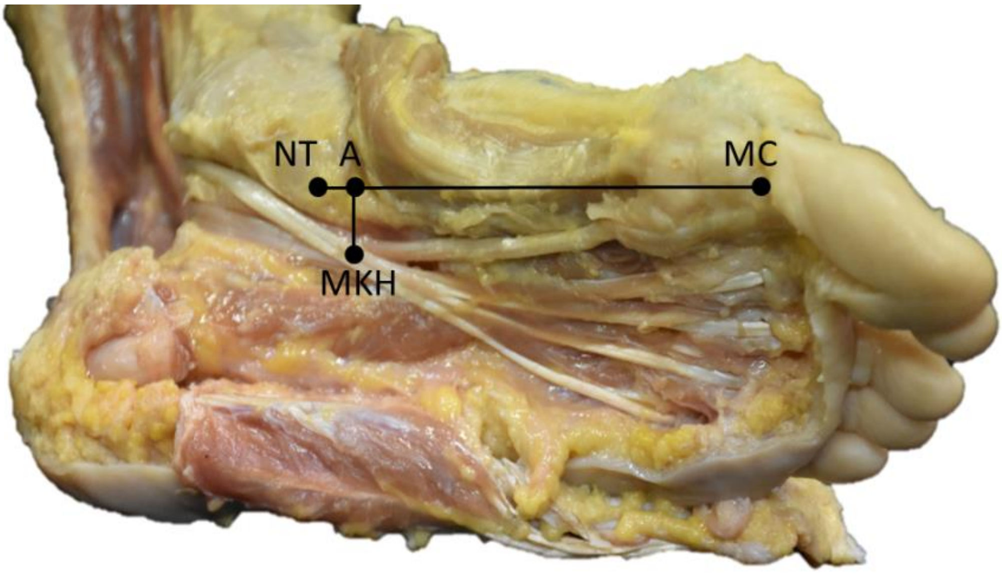


Figure 58 Photograph of left foot demonstrated the location of point A resided anterior to NT on MC-NT line.

(A: perpendicular point of MKH on MC-NT line, MC: medial end of plantar flexion crease at the base of the great toe, MKH: master knot of Henry, NT: navicular tuberosity)

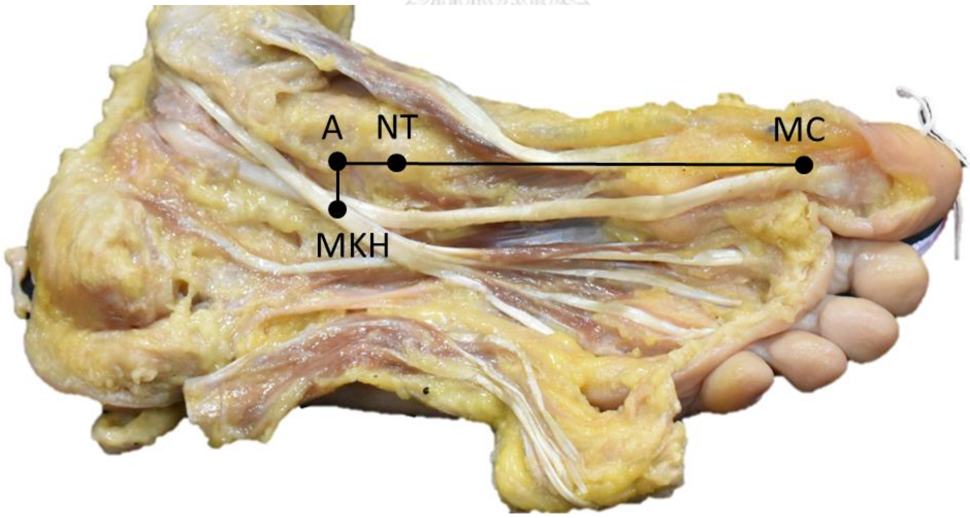


Figure 59 Photograph of left foot demonstrated the location of point A resided posterior to NT on MC-NT line

(A: perpendicular point of MKH on MC-NT line, MC: medial end of plantar flexion crease at the base of the great toe, MKH: master knot of Henry, NT: navicular tuberosity)

Table 15 Length of MC-NT, MKH-A, and MC-A

Surface landmark	Length (mm) mean ± SD (min-max)								
	Male				Female				Total (n=62)
	Left (n=9)	Right (n=9)	Total (n=18)	Difference between sides	Left (n=22)	Right (n=22)	Total (n=44)	Difference between sides	
MC-NT	113.11±10.21 (91.75 – 124.12)	113.13±7.44 (101.49 – 122.19)	113.12±8.67 (91.75 – 123.37)	*p*-value = 0.995	102.57±8.09 (87.18 – 116.74)	107.45±6.01 (97.26 – 117.65)	105.01±7.46 (87.18 – 117.65)	*p*-value = 0.006	107.36±8.60 (87.18 – 124.12)
Difference between genders - Left - Right	*p*-value = 0.005 *p*-value = 0.034								
MKH-A	29.10±8.83 (19.39 – 41.85)	27.89±4.86 (25.11 – 35.53)	28.49±6.94 (19.39 – 41.85)	*p*-value = 0.708	24.18±3.33 (17.26 – 32.27)	23.26±4.39 (16.89 – 34.15)	23.72±3.88 (16.89 – 34.15)	*p*-value = 0.213	25.11±5.37 (16.89 – 41.85)
Difference between genders - Left - Right	*p*-value = 0.655 *p*-value = 0.015								
MC-A	111.59±11.01 (90.62 – 126.71)	110.87±15.39 (87.26 – 139.77)	111.23±12.99 (87.26 – 139.77)	*p*-value = 0.881	95.92±10.55 (76.05 – 116.74)	99.75±7.40 (86.91 – 115.63)	97.83±9.21 (76.05 – 116.74)	*p*-value = 0.074	101.72±12.01 (76.05 – 139.77)
Difference between genders - Left - Right	*p*-value = 0.426 *p*-value = 0.024								

(A: perpendicular point of MKH on MC-NT line, MC: medial end of plantar flexion crease at the base of great toes, MKH: master knot of Henry)

Surface localization of MKH (point A) was analyzed in term of percentage of MC-NT length from MC (Table 16). In male, point A was located at 98.59±11.98 % of MC-NT length. In female, the mean location of point A was defined at 93.18±5.95 % of MC-NT length. No significant difference was found between sides and between genders.

Table 16 Location of MKH (A) in term of percentage of the length of MC-NT

Genders/Sides	% mean ± SD (min-max)			Difference between sides
	Left	Right	Total	
Male	(n=9) 98.84±7.22 (87.77-110.29)	(n=9) 98.34±15.90 (82.21-137.72)	(n=18) 98.59±11.98 (82.21-137.72)	0.327
Female	(n=22) 93.47±6.36 (75.82-107.16)	(n=22) 92.89±5.65 (79.82-100.00)	(n=44) 93.18±5.95 (75.82-107.16)	0.616
Total	(n=31) 95.03±6.96 (75.82-110.29)	(n=31) 94.47±9.80 (79.82-137.72)	(n=62) 94.75±8.43 (75.82-137.72)	-
Difference between genders	0.050	0.537	-	

(A= perpendicular point of MKH on MC-NT line)

4.7 Relationship between MKH and plantar neurovascular bundle

The MPNVB lied very closely to MKH in all cases; therefore, no distance could be measured (Figure 60). In contrast, a mean distance of 17.13±3.55 mm was observed between LPNVB and MKH without a statistically significant difference between genders. However, a statistically significant difference was found between sides in female (p = 0.024) (Table 17).

Table 17 Distance between MKH and plantar neurovascular bundles

Neurovascular bundle	Distance (mm) mean ± SD (min-max)								
	Male			Difference between sides	Female			Difference between sides	Total (n=62)
	Left (n=9)	Right (n=9)	Total (n=18)		Left (n=22)	Right (n=22)	Total (n=44)		
LPNVB	17.98±6.09 (9.59 – 30.29)	19.91±5.32 (13.05 – 28.85)	18.95±5.64 (9.59 – 30.29)	*p*-value = 0.512	15.17±3.84 (8.44 – 22.05)	17.61±3.56 (7.11 – 24.38)	16.39±3.86 (7.11 – 24.38)	*p*-value = 0.024	17.13±3.55 (7.11 – 30.29)
Difference between genders - Left - Right	*p*-value = 0.131 *p*-value = 0.168								
MPNVB	0	0	-		0	0	-		-

(LPNVB: lateral plantar neurovascular bundle, MPNVB: medial plantar neurovascular bundle)

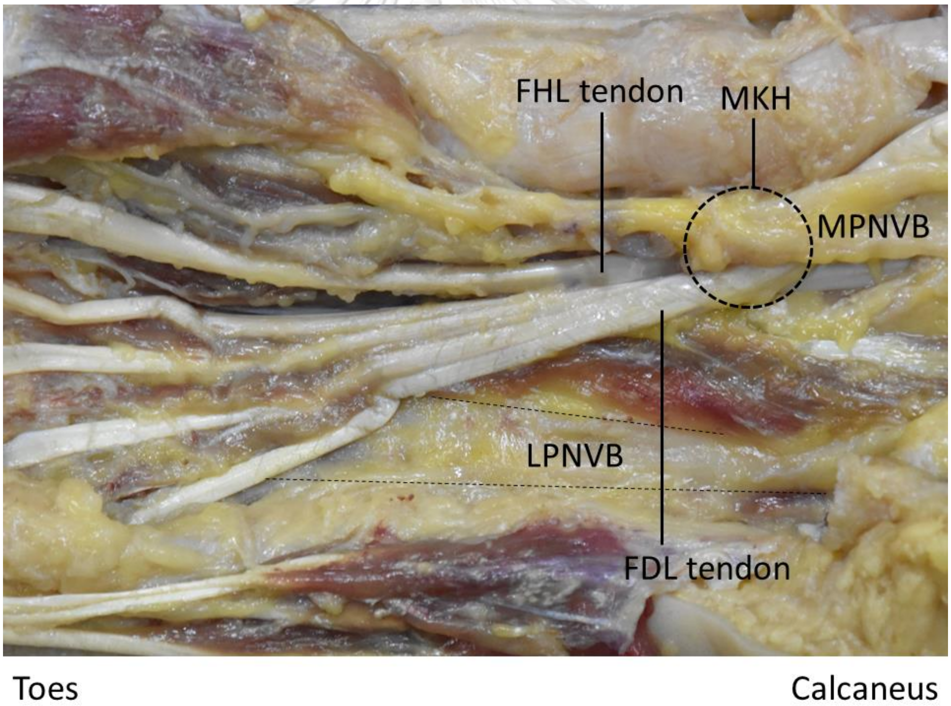


Figure 60 Right plantar surface of foot showed the relationship between MKH and neurovascular bundle (MPNVB and LPNVB)

(FDL: flexor digitorum longus, FHL: Flexor hallucis longus, LPNVB: lateral plantar neurovascular bundles, MKH: master knot of Henry, MPNVB: medial plantar neurovascular bundles)

4.8 Type of tendinous interconnection between FHL and FDL

Type of tendinous interconnection was examined in 164 specimens. According to Beger et al., three types of tendinous interconnection (type I, II, V) were found (Table 18, Figure 61-66).The most frequent was type I (82.93 %) followed by type V (7.93%) and type II (0.61%) respectively. In addition, a new type of interconnection (8.54%) in which FHL tendon was bifurcated and sent one tendon to the first toe and the other tendon fused with FDL tendon (Figure 67-68). Symmetrical type of tendinous interconnection was found in 79.27% of cases. The prevalence of each type is shown in Table 19.

Table 18 Prevalence of tendinous interconnection type between FHL and FDL

Type	n (%)														
	Soft cadavers							Embalmed cadavers							Total (164)
	Male			Female			Total (62)	Male			Female			Total (102)	
	Left (9)	Right (9)	Total (18)	Left (22)	Right (22)	Total (44)		Left (32)	Right (32)	Total (64)	Left (19)	Right (19)	Total (38)		
I	6 (3.66)	7 (4.27)	13 (7.93)	17 (10.36)	16 (9.76)	33 (20.12)	46 (28.05)	28 (17.07)	27 (16.47)	55 (33.54)	16 (9.76)	19 (11.58)	35 (21.34)	90 (54.88)	136 (82.93)
II	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (0.61)	0 (0)	1 (0.61)	0 (0)	0 (0)	0 (0)	1 (0.61)	1 (0.61)
III	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
IV	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
V	2 (1.22)	0 (0)	2 (1.22)	1 (0.61)	2 (1.22)	3 (1.83)	5 (3.05)	2 (1.22)	4 (2.44)	6 (3.66)	2 (1.22)	0 (0)	2 (1.22)	8 (4.88)	13 (7.93)
VI	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
VII	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Other	1 (0.61)	2 (1.22)	3 (1.83)	4 (2.44)	4 (2.44)	8 (4.88)	11 (6.71)	1 (0.61)	1 (0.61)	2 (1.22)	1 (0.61)	0 (0)	1 (0.61)	3 (1.83)	14 (8.54)

Table 19 Prevalence of symmetrical type of tendinous interconnection between FHL and FDL tendons

Types	n (%)		
	Male	Female	Total
Symmetry			
I	29 (35.37%)	31 (37.80%)	60 (73.17%)
II	0 (0%)	0 (0%)	0 (0%)
V	0 (0%)	1 (1.22%)	1 (1.22%)
Other	1 (1.22%)	3 (3.66%)	4 (4.88%)
Total	30 (36.59%)	35 (42.68%)	65 (79.27%)
Asymmetry			
I &II	1 (1.22%)	0 (0%)	1 (1.22%)
I&V	7 (8.54%)	3 (3.66%)	10(12.20%)
I & Other	2 (2.44%)	3 (3.66%)	5 (6.10%)
II&V	0 (0%)	0 (0%)	0 (0%)
II& Other	0 (0%)	0 (0%)	0 (0%)
V& Other	1 (1.22%)	0 (0%)	1 (1.22%)
Total	11 (13.41%)	6 (7.32%)	17 (20.73%)

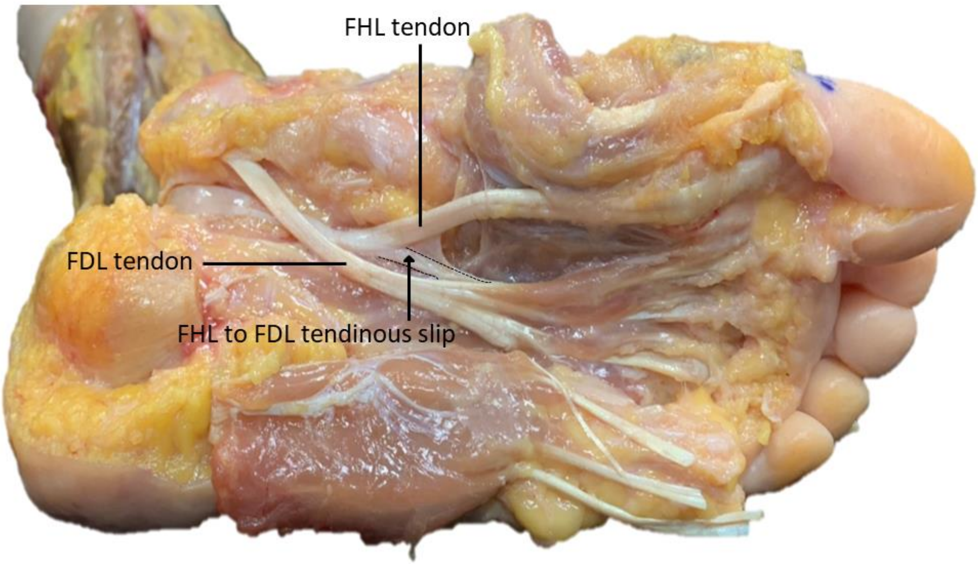


Figure 61 Left plantar surface of foot showing type I of tendinous interconnection with a slip from FHL to FDL tendon.

(FDL: flexor digitorum longus, FHL: Flexor hallucis longus)

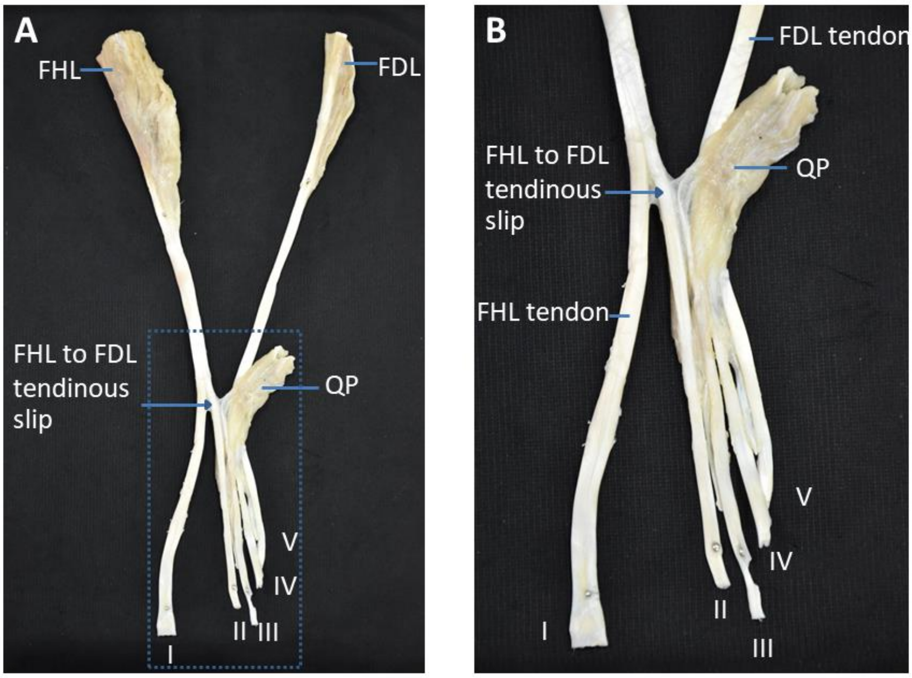


Figure 62 FHL and FDL with type I tendinous interconnection**.** A. Lower magnification; B. Higher magnification.

(FDL: flexor digitorum longus, FHL: flexor hallucis longus, QP: quadratus plantae)

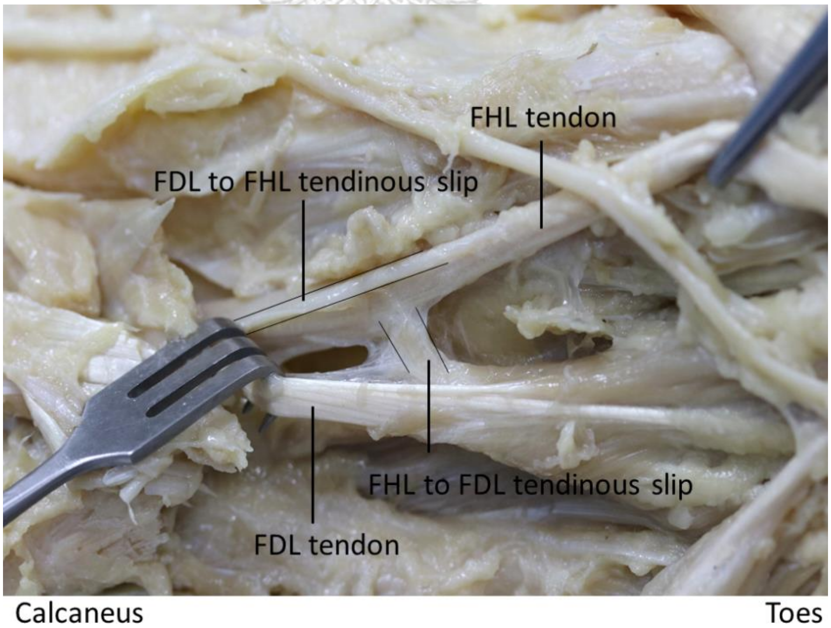


Figure 63 Left plantar surface of foot showing type II of tendinous interconnection with two slips, one from FHL to FDL tendon and the other from FDL to FHL tendon

(FDL: flexor digitorum longus, FHL: flexor hallucis longus)

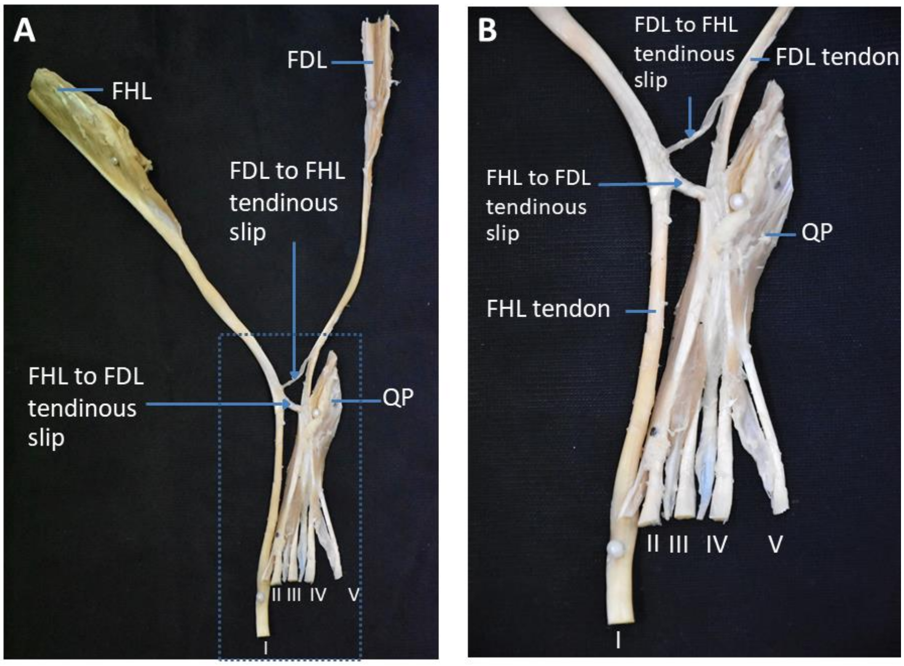


Figure 64 FHL and FDL with type II of tendinous interconnection showing two tendinous slips, one from FHL to FDL tendon and the other slip from FDL to FHL tendon**.** A. Lower magnification; B. Higher magnification.

(FDL: flexor digitorum longus, FHL: flexor hallucis longus, QP: quadratus plantae)

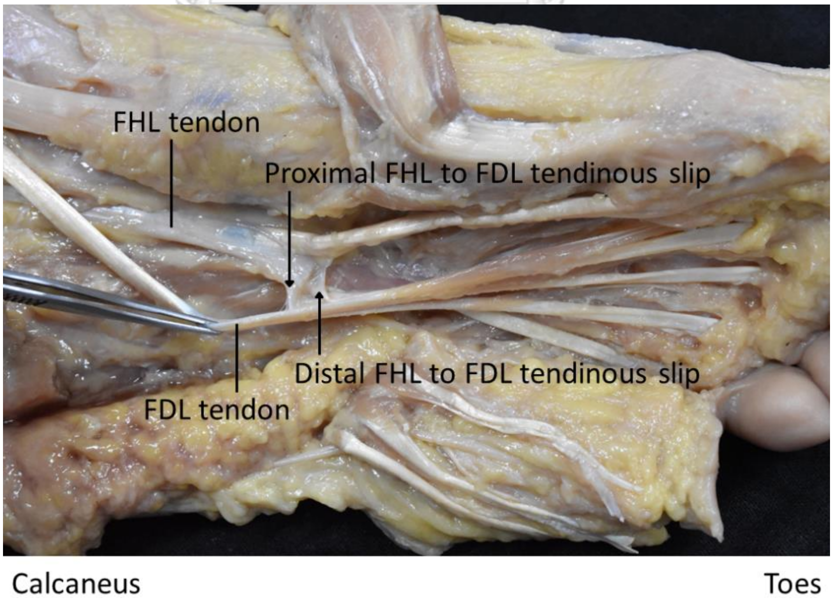


Figure 65 Left plantar surface of foot showing type V of tendinous interconnection with double slip from FHL to FDL tendon

(FDL: flexor digitorum longus, FHL: flexor hallucis longus)

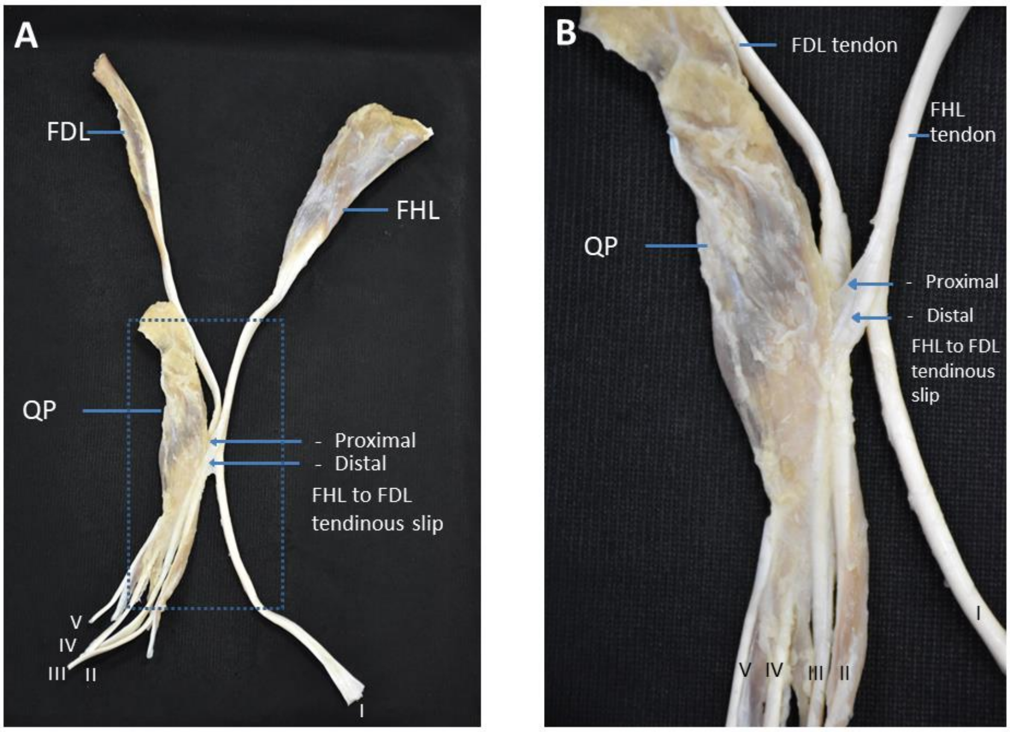


Figure 66 FHL and FDL with type V of tendinous interconnection showing two tendinous slips from FHL to FDL tendon. A. Lower magnification; B. Higher magnification.

(FDL: flexor digitorum longus, FHL: flexor hallucis longus, QP: quadratus plantae)

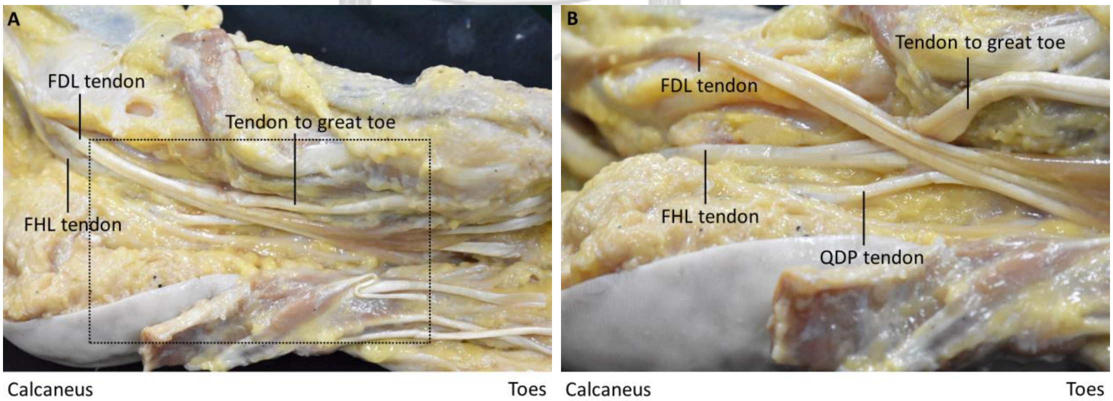


Figure 67 Left plantar surface of foot showing the new type of tendinous interconnection between FHL and FDL. FHL tendon was bifurcated and sent one tendon to the great toe and the other tendon fused with FDL tendon**:** A. Lower magnification; B. Higher magnification with turning up of FDL tendon.

(FDL: flexor digitorum longus, FHL: flexor hallucis longus)

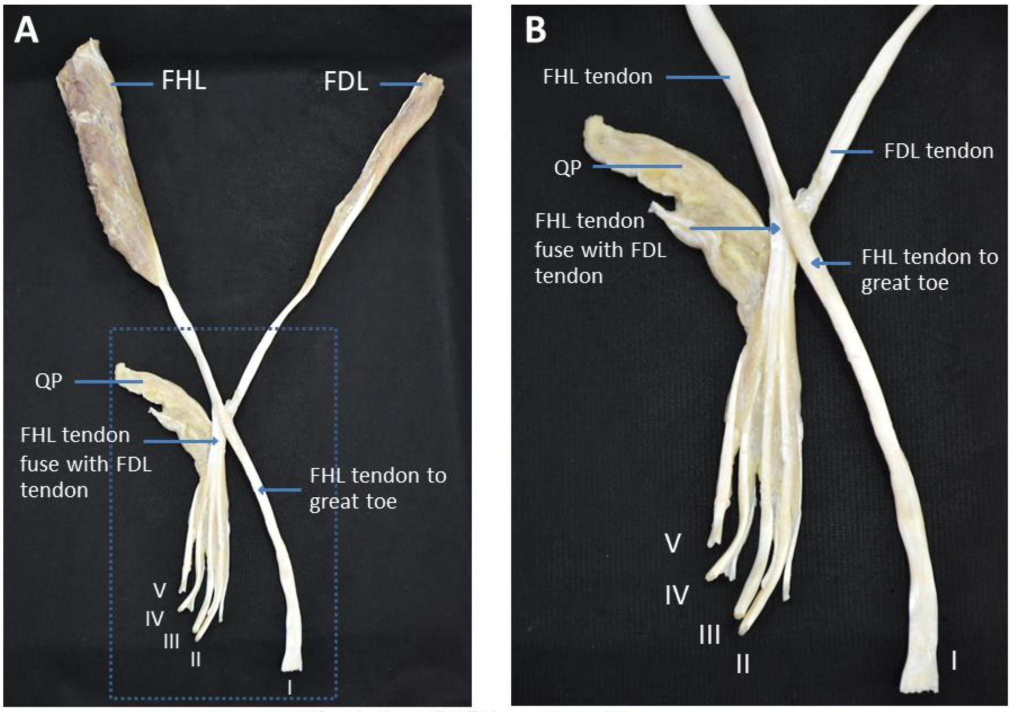


Figure 68 New type of FHL and FDL tendinous interconnection showing a tendinous slip from FHL fused with FDL tendon. A. Lower magnification; B. Higher magnification.
(FDL: flexor digitorum longus, FHL: flexor hallucis longus, QP: quadratus plantae)

4.9 Location of tendinous interconnection

The location of tendinous interconnection was investigated in 62 specimens of soft cadavers. It was located either proximal (-) or distal (+) to MKH (Table 20). The mean distance from MKH in type I was 0.27±15.37 mm. The proximal and distal interconnection slips in type V were located at 6.61±4.69 mm and 12.95±3.48 mm from MKH, respectively. The bifurcation FHL tendon in the new type was located at 0.97±13.04 mm from MKH. No statistically significant difference was found between genders and sides.

Table 20 Location of tendinous interconnection (distance from MKH to branching point of tendinous interconnection)

Type of tendinous interconnection	Distance (mm) mean ± SD (min-max)								
	Male				Female				Total (n=62)
	Left	Right	Total	Difference between sides	Left	Right	Total	Difference between sides	
Type I - proximal slip	(n=6) -2.15±25.76 (-54.39 – 12.34)	(n=7) -4.58±25.00 (-59.47 – 14.96)	(n=13) -3.32±24.29 (-59.47 – 14.96)	*p*-value = 0.345	(n=17) 2.20±11.07 (-21.33 – 18.06)	(n=16) 1.13±9.46 (-15.75 – 18.65)	(n=33) 1.68±10.17 (-21.33 – 18.65)	*p*-value = 0.923	(n=46) 0.27±15.37 (-59.47 – 18.65)
Difference between genders - Left - Right	*p*-value =0.726 *p*-value =0.892								
Type V - proximal slip - distal slip	(n=2) 4.50±6.36 (0.00 – 9.00) 14.25±0.26 (14.07 – 14.44)	-	(n=2) 4.50±6.36 (0.00 – 9.00) 14.25±0.26 (14.07 – 14.44)	- -	(n=1) 12.47 16.13	(n=2) 5.80±1.72 (4.59 – 7.02) 10.05±4.24 (7.05 – 13.05)	(n=3) 8.02±4.04 (4.59 – 12.47) 12.08±4.62 (7.05 – 16.13)	- -	(n=5) 6.61±4.69 (0.00 – 12.47) 12.95±3.48 (7.05 – 16.13)
Difference between genders Proximal slip - Left - Right Distal slip - Left - Right	*p*-value = 0.493 - *p*-value = **0.106** -								
Other - proximal slip	(n=1) -9.04	(n=2) -1.63±27.14 (-20.81 - 17.56)	(n=3) -4.10±19.66 (-20.81 - 17.56)	-	(n=4) 6.05±5.58 (0.00 – 13.52)	(n=4) -0.31±14.81 (-11.36 –2 0.52)	(n=8) 2.87±10.91 (-11.36 - 20.52)	*p*-value = **0.704**	(n=11) 0.97±13.04 (-20.81 - 20.52)
Difference between genders Proximal slip - Left - Right	*p*-value = **0.094** *p*-value = **0.939**								
All types - Proximal slip - Distal slip	(n=9) -1.44±20.89 (-54.39 – 12.34) (n=2) 14.25±0.26 (14.07 – 14.44)	(n=9) -3.72±23.72 (-59.47 – 17.56 -	(n=18) -2.58±21.71 (-59.47 – 17.56) (n=2) 14.25±0.26 (14.07 – 14.44)	*p*-value = **0.441** -	(n=22) 3.37±10.21 (-21.33 – 18.06) (n=1) 16.13	(n=22) 1.29±9.89 (-15.75 – 20.52) (n=2) 10.05±4.24 (7.05 – 13.05)	(n=44) 2.33±9.99 (-21.33 – 20.52) (n=3) 12.08±4.62 (7.05 – 16.13)	*p*-value = **0.431** -	(n=62) 0.90±14.38 (-59.47 - 20.52) (n=5) 12.95±3.48 (7.05 - 16.13)
Difference between genders Proximal slip - Left - Right Distal slip - Left - Right	*p*-value =0.777 *p*-value =0.982 *p*-value =**0.106** -								

4.10 Width of tendinous interconnection

The width of tendinous interconnection at branching point in each type is shown in table 21. Mean width of slip in type I was 3.78±1.12 mm. In type V, the mean width of proximal slip was 2.05±0.48 mm and distal slip was 2.77±0.41 mm. The mean width of slip in new type was 4.12±0.57 mm. No statistically significance differences between genders were found in all types. The statistically significant differences between sides was found in new type of female (*p*=0.041).

Table 21 Width of tendinous interconnection at branching point in each type of tendinous interconnection

Type of tendinous interconnection	Width (mm) mean ± SD (min-max) Male Left	 Right	 Total	 Difference between sides	 Female Left	 Right	 Total	 Difference between sides	 Total (n=61)
Type I - proximal slip	(n=6) 3.63±0.67 (2.57 – 4.28)	(n=7) 3.85±1.22 (2.15 – 6.02)	(n=13) 3.75±0.97 (2.15 – 6.02)	*p*-value = 0.509	(n=17) 3.63±0.96 (2.15 – 5.57)	(n=15) 3.98±1.42 (2.25 – 7.76)	(n=32) 3.79±1.20 (2.15 – 7.76)	*p*-value = 0.594	(n=45) 3.78±1.12 (2.15 – 7.76)
Difference between genders - Left - Right	*p*-value =0.996 *p*-value =0.944								
Type V - proximal slip - distal slip	(n=2) 2.34±0.56 (1.94 – 2.73) 3.04±0.11 (2.96 – 3.12)	- -	(n=2) 2.33±0.56 (1.94 – 2.73) 3.04±0.11 (2.96 – 3.12)	- -	(n=1) 2.32 2.32	(n=2) 1.63±0.64 (1.58 – 1.67) 2.72±0.56 (2.32 – 3.11)	(n=3) 1.86±0.40 (1.58 – 2.32) 2.58±0.4 6(2.32 – 3.11)	- -	(n=5) 2.05±0.48 (1.58 – 2.73) 2.77±0.41 (2.32 – 3.12)
Difference between genders Proximal slip - Left - Right Distal slip - Left - Right	*p*-value =0.986 *p*-value = - *p*-value =0.121 *p*-value = -								
Other - proximal slip	(n=1) 4.96	(n=2) 3.69±0.77 (3.15 – 4.24)	(n=3) 4.12±0.91 (3.15 – 4.96)	-	(n=4) 3.85±0.42 (3.51 – 4.46)	(n=4) 4.38±0.417 (4.10 – 4.99)	(n=8) 4.12±0.48 (3.51 – 4.99)	*p*-value = 0.041	(n=11) 4.12±0.57 (3.15 – 4.99)
Difference between genders Proximal slip - Left - Right	*p*-value =0.099 *p*-value =0.206								
All types - Proximal slip - Distal slip	(n=9) 3.49±0.97 (1.94 – 4.96) (n=2) 3.04±0.11 (2.96 – 3.12)	(n=9) 3.82±1.09 (2.15 – 6.02) -	(n=18) 3.65±1.02 (1.94 – 6.02) (n=2) 3.04±0.11 (2.96 – 3.12)	*p*-value = 0.467 -	(n=22) 3.61±0.90 (2.15 – 5.57) (n=1) 2.32	(n=21) 3.83±1.41 (1.58 – 7.76) (n=2) 2.72±0.56 (2.32 – 3.11)	(n=43) 3.72±1.17 (1.58 – 7.76) (n=3) 2.58±0.46 (2.32 – 3.11)	*p*-value = 0.520 -	(n=61) 3.70±1.12 (1.58 - 7.76) (n=5) 2.92±0.52 (2.32 - 3.66)
Difference between genders Proximal slip - Left - Right Distal slip - Left - Right	*p*-value =0.739 *p*-value =0.976 *p*-value =0.121 *p*-value = -								

4.11 Distribution of tendinous interconnection

Distribution of tendinous interconnection to lesser toes was determined by observing the movement of FDL and FHL tendons while moving each toe according to the method used by Plaass et al [30]. The prevalence of each type is shown in table 22. The most common was type b followed by type a, c and d. Symmetrical type of slip distribution to lesser toes was found in 74.39% of specimens and the most frequency was type b (Table 23). No correlation between width of both proximal and distal slips and type of slip distribution to lesser toes (r = 0.177, -0. 243).

Table 22 Prevalence of type of slip distribution to lesser toes from FDL and FHL tendons movement while moving toes

Type	n (%)														
	Soft cadavers							Embalmed cadavers							Total (164)
	Male			Female			Total (62)	Male			Female			Total (102)	
	Left (9)	Right (9)	Total (18)	Left (22)	Right (22)	Total (44)		Left (32)	Right (32)	Total (64)	Left (19)	Right (19)	Total (38)		
a	3 (1.83)	3 (1.83)	6 (3.66)	3 (1.83)	4 (2.44)	7 (4.27)	13 (7.93)	8 (4.88)	4 (2.44)	12 (7.32)	3 (1.83)	4 (2.44)	7 (4.27)	19 (11.59)	32 (19.51)
b	6 (3.66)	5 (3.05)	11 (6.71)	18 (10.98)	13 (7.93)	31 (18.90)	42 (25.61)	19 (11.58)	23 (14.02)	42 (25.61)	14 (8.54)	13 (7.93)	27 (16.46)	69 (42.07)	111 (67.68)
c	0 (0)	1 (0.61)	1 (0.61)	1 (0.61)	5 (3.05)	6 (3.66)	7 (4.27)	5 (3.05)	5 (3.05)	10 (6.10)	0 (0)	1 (0.61)	1 (0.61)	11 (6.71)	18 (10.98)
d	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	2 (1.22)	1 (0.61)	3 (1.83)	3 (1.83)	3 (1.83)

Table 23 Prevalence of symmetrical type of slip distribution to lesser toes from FDL and FHL tendons movement while moving toes

	n (%)		
	Male	Female	Total
Symmetry			
a&a	6 (7.32%)	4 (4.88%)	10 (12.20%)
b&b	22 (26.83%)	23 (28.05%)	45 (54.88%)
c&c	4 (4.88%)	1 (1.22%)	5 (6.10%)
d&d	0 (0%)	1 (1.22%)	1 (1.22%)
total	32 (39.03%)	29 (35.37%)	61 (74.39%)
Asymmetry			
a&b	6 (7.32%)	6 (7.32%)	12(14.64%)
a&c	0 (0%)	0 (0%)	0 (0%)
a&d	0 (0%)	0 (0%)	0 (0%)
b&c	3 (3.66%)	5 (6.10%)	8 (9.76%)
b&d	0 (0%)	1 (1.22%)	1 (1.22%)
c&d	0 (0%)	0 (0%)	0 (0%)
Total	9 (10.98%)	12 (14.64%)	21 (25.61%)

4.12 Length of FHL tendon

The mean in situ and ex vivo lengths of FHL tendon grafts, which were harvested by three different incision techniques, were displayed in Table 24-25. The in situ and ex vivo lengths of MTJ-ST which represent the tendon graft from single incision technique were 3.90±1.09 and 3.44±1.02 cm, respectively. According to double incision technique, the length of MTJ-MKH from in situ was 7. 34±0.99 cm and from ex vivo was 6.86±0.94 cm. The lengths of in situ and ex vivo tendon graft from MTJ to IP, which referred tendon graft from minimally invasive technique, were 19.80±1.39 and 19.18±1.40 cm. In comparing the lengths of FHL tendon graft, the difference between genders was found to be statistically significant in MTJ-IP of in situ and ex vivo length in both sides ($p < 0.05$). The mean length of tendon between in situ and ex vivo was significantly different in all techniques ($p < 0.05$).

Table 24 In situ length of FHL tendon from single posterior medial (MTJ-ST), double (MTJ-MKH), and minimally invasive (MTJ-IP) techniques.

Techniques / Genders	Length (cm) mean ± SD (min-max)								
	Male				Female				Total (n=62)
	Left (n=9)	Right (n=9)	Total	Difference between sides	Left (n=22)	Right (n=22)	Total	Difference between sides	
MTJ-ST	4.32±1.21 (2.10 – 6.00)	4.16±0.84 (3.00 – 5.50)	4.24±1.01 (2.10 – 6.00)	*p*-value = 0.131	3.75±1.01 (1.50 – 6.20)	3.79±1.20 (1.90 – 7.10)	3.77±1.10 (1.50 – 7.10)	*p*-value = 0.601	3.90±1.09 (1.50 – 7.10)
Difference between genders - Left - Right	*p*-value =0.106 *p*-value =0.408								
MTJ-MKH	7.68±0.95 (6.70 – 9.50)	7.58±1.02 (6.00 – 9.10)	7.63±0.96 (6.00 – 9.50)	*p*-value = 0.812	7.10±0.81 (5.90 – 9.20)	7.35±1.15 (5.40 – 9.50)	7.23±0.99 (5.40 – 9.50)	*p*-value = 0.191	7.34±0.99 (5.40 – 9.50)
Difference between genders - Left - Right	*p*-value =0.097 *p*-value =0.624								
MTJ-IP	20.94±1.77 (18.10 – 24.00)	20.96±1.53 (18.80 – 24.00)	20.95±1.60 (18.10 – 24.00)	*p*-value = 0.949	19.22±0.91 (17.40 – 21.50)	19.22±1.03 17.90 – 21.50)	19.33±0.97 (17.40 – 21.50)	*p*-value = 0.279	19.80±1.39 (17.40 – 24.00)
Difference between genders - Left - Right	*p*-value = 0. 001 *p*-value = 0.017								

(IP: first interphalangeal joint, MKH: master knot of Henry, MTJ: musculotendinous junction, ST: sustentaculum tali)

Table 25 Ex vivo length of FHL tendon from single posterior medial (MTJ-ST), double (MTJ-MKH), and minimally invasive (MTJ-IP) techniques.

<table>
<tr><td rowspan="3">Techniques / Genders</td><td colspan="9">Length (cm)
mean ± SD (min-max)</td></tr>
<tr><td colspan="4">Male</td><td colspan="4">Female</td><td rowspan="2">Total
(n=62)</td></tr>
<tr><td>Left
(n=9)</td><td>Right
(n=9)</td><td>Total</td><td>Difference between sides</td><td>Left
(n=22)</td><td>Right
(n=22)</td><td>Total</td><td>Difference between sides</td></tr>
<tr><td>MTJ-ST</td><td>3.83±1.02
(1.90 – 5.00)</td><td>3.67±0.74
(2.50 – 4.60)</td><td>3.75±0.87
(1.90 – 5.00)</td><td>p-value
= 0.532</td><td>3.30±1.06
(1.10 – 5.70)</td><td>3.34±1.09
(1.50 – 5.80)</td><td>3.32±1.06
(1.10 – 5.80)</td><td>p-value
= 0.861</td><td>3.44±1.02
(1.10 – 5.80)</td></tr>
<tr><td>Difference between genders
- Left
- Right</td><td colspan="8">p-value = 0.210
p-value = 0.412</td><td></td></tr>
<tr><td>MTJ-MKH</td><td>7.16±0.89
(6.40 – 9.00)</td><td>7.04±0.94
(5.70 – 8.70)</td><td>7.11±0.89
(5.70 – 9.00)</td><td>p-value
= 0.760</td><td>6.64±0.87
(5.40 – 8.90)</td><td>6.88±1.04
(5.10 – 8.40)</td><td>6.76±0.96
(5.10 – 8.90)</td><td>p-value
= 0.256</td><td>6.86±0.94
(5.10 – 9.00)</td></tr>
<tr><td>Difference between genders
- Left
- Right</td><td colspan="8">p-value = 0.144
p-value = 0.688</td><td></td></tr>
<tr><td>MTJ-IP</td><td>20.36±1.87
(17.40 – 23.60)</td><td>20.37±1.49
(18.40 – 23.50)</td><td>20.37±1.65
(17.40 – 23.60)</td><td>p-value
= 0.912</td><td>18.64±0.92
(16.70 – 20.90)</td><td>18.75±0.97
(17.30 – 20.50)</td><td>18.69±0.94
(16.70 – 20.90)</td><td>p-value
= 0.456</td><td>19.18±1.40
(16.70 – 23.60)</td></tr>
<tr><td>Difference between genders
- Left
- Right</td><td colspan="8">p-value = 0.002
p-value = 0.001</td><td></td></tr>
</table>

(IP: first interphalangeal joint, MKH: master knot of Henry, MTJ: musculotendinous junction, ST: sustentaculum tali)

The mean different length between in situ and ex vivo tendon length in single incision, double incision and minimal invasive techniques was 0.46±0.24 , 0.48±0.21, and 0.62±0.30 mm without the significant difference between genders and between sides (Table 26).

Table 26 Different length between in situ and ex vivo length of FHL tendon in single posterior medial (MTJ-ST), double (MTJ-MKH), and minimally invasive (MTJ-IP) techniques.

Techniques / Genders	Length (cm) mean ± SD (min-max)								
	Male				Female				Total (n=62)
	L(n=9)	R (n=9)	Total	Difference between sides	L (n=22)	R (n=22)	Total	Difference between sides	
MTJ-ST	0.49±0.27 (0.20 – 1.00)	0.49±0.28 (0.20 – 1.00)	0.49±0.26 (0.20 – 1.00)	*p*-value = 0.932	0.45±0.22 (0.10 – 1.00)	0.45±0.24 (0.00 – 1.30)	0.45±0.23 (0.00 – 1.30)	*p*-value = 0.749	0.46±0.24 (0.00 – 1.30)
Difference between genders - Left - Right	*p*-value =0.774 *p*-value =0.894								
MTJ-MKH	0.51±0.16 (0.30 – 0.80)	0.53±0.20 (0.30 – 1.00)	0.52±0.18 (0.30 – 1.00)	*p*-value = 0.523	0.45±0.23 (0.10 – 1.00)	0.48±0.21 (0.00 – 1.10)	0.47±0.22 (0.00 – 1.10)	*p*-value = 0.766	0.48±0.21 (0.00 – 1.10)
Difference between genders - Left - Right	*p*-value =0.502 *p*-value =0.461								
MTJ-IP	0.59±0.20 (0.40 – 1.00)	0.58±0.25 (0.30 – 1.00)	0.58±0.22 (0.30 – 1.00)	*p*-value = 0.915	0.59±0.25 (0.20 – 1.30)	0.68±0.38 (0.30 – 1.60)	0.63±0.32 (0.20 – 1.60)	*p*-value = 0.261	0.62±0.30 (0.20 – 1.60)
Difference between genders - Left - Right	*p*-value =0.979 *p*-value =0.685								

(IP: first interphalangeal joint, MKH: master knot of Henry, MTJ: musculotendinous junction, ST: sustentaculum tali)

The length of FHL tendon was calculated in term of percentage of foot length as shown in Table 27. In situ and ex vivo tendon lengths were 16.96±4.84 and 14.96±4.53%, 31.88±4.43 and 29.79±4.16%, 85.63±3.70 and 83.09±3.90% of foot length in single incision, double incision, and minimally invasive techniques, respectively. The statistical significant differences between sides and between genders were not observed.

Table 27 Length of harvested FHL tendon in term of percentage of the foot length

Techniques / Genders	% mean ± SD (min-max)								Total (n=62)
	Male				Female				
	Left (n=9)	Right (n=9)	Total (n=18)	Difference between sides	Left (n=22)	Right (n=22)	Total (n=44)	Difference between sides	
• In situ length MTJ-ST	17.45±4.64 (9.33 – 24.29)	16.84±3.27 (12.24 – 22.82)	17.14±3.90 (9.33– 24.29)	*p*-value = 0.513	16.84±4.72 (6.38 – 28.84)	16.92±5.77 (8.19 – 33.81)	16.88±5.21 (6.38 – 33.81)	*p*-value = 0.929	16.96±4.84 (6.38 – 33.81)
Difference between genders - Left - Right	*p*-value =0.745 *p*-value =1.000								
MTJ-MKH	31.18±3.69 (27.31– 35.56)	30.76±2.91 (26.15 – 36.93)	30.97±3.79 (26.15 – 36.93)	*p*-value = 0.859	31.81±3.89 (25.11 – 39.07)	32.70±5.36 (23.40 – 45.24)	32.26±4.65 (23.40 – 45.24)	*p*-value = 0.312	31.88±4.43 (23.40 – 45.24)
Difference between genders - Left - Right	*p*-value =0.677 *p*-value =0.338								
MTJ-IP	84.89±3.89 (74.58 – 88.06)	84.97±3.90 (80.77 – 93.36)	84.93±3.78 (78.75 – 93.36)	*p*-value = 0.928	86.02±3.91 (75.74 – 92.09)	85.83±3.51 (79.91 – 93.75)	85.92±3.67 (75.74 – 93.75)	*p*-value = 0.213	85.63±3.70 (75.74 – 93.75)
Difference between genders - Left - Right	*p*-value =0.471 *p*-value =0.555								
• Ex vivo length MTJ-ST	15.47±3.85 (8.44 – 20.24)	14.87±2.91 (12.24 – 18.67)	15.17±3.33 (8.44 – 20.24)	*p*-value = 0.558	14.83±4.91 (4.78 – 26.51)	14.91±5.15 (6.47 – 27.62)	14.87±4.97 (4.78 – 27.62)	*p*-value = 0.927	14.96±4.53 (4.78 – 27.62)
Difference between genders - Left - Right	*p*-value =0.727 *p*-value =0.982								
MTJ-MKH	29.09±3.31 (25.77 – 33.58)	28.59±3.70 (24.23 – 34.80)	28.84±3.41 (24.23 – 34.80)	*p*-value = 0.674	29.77±4.07 (23.20 – 37.21)	30.57±4.78 (23.18 – 40.00)	32.26±4.65 (23.18 – 40.00)	*p*-value = 0.356	29.79±4.16 (23.18 – 40.00)
Difference between genders - Left - Right	*p*-value =0. 660 *p*-value =0.275								
MTJ-IP	82.48±4.49 (74.58 – 88.06)	82.61±3.34 (79.62 – 89.21)	82.55±3.84 (74.58 – 89.21)	*p*-value = 0.895	83.38±3.71 (74.89 – 90.23)	83.38±3.71 (74.89 – 90.23)	83.31±3.95 (74.89 – 94.76)	*p*-value = 0.846	83.09±3.90 (74.58 – 94.76)
Difference between genders - Left - Right	*p*-value =0.568 *p*-value =0.694								

(IP: first interphalangeal joint, MKH: master knot of Henry, MTJ: musculotendinous junction, ST: sustentaculum tali)

4.13 Correlation between foot length and tendon length

The correlation between foot length and tendon graft length was presented in table 28-29. Moderate positive correlation between foot length and tendon length was found in MTJ-IP of both in situ and ex vivo tendon length (r = 0.753, 0.779).

Table 28 Correlation between foot length and in situ length of FHL tendon

	Pearson correlation co-efficiency						
	Male			Female			Total (n=62)
	Left (n=9)	Right (n=9)	Total (n=18)	Left (n=22)	Right (n=22)	Total (n=44)	
MTJ-ST	0.549	0.344	0.454	-0.146	-0.328	-0.237	0.093
MTJ-MKH	0.304	0.233	0.266	0.014	0.057	0.047	0.201
MTJ-IP	0.896	0.781	0.839	0.593	0.449	0.520	0.753

(IP: first interphalangeal joint, MKH: master knot of Henry, MTJ: musculotendinous junction, ST: sustentaculum tali)

Table 29 Correlation between foot length and ex-vivo length of FHL tendon

	Pearson correlation co-efficiency						
	Male			Female			Total (n=62)
	Left (n=9)	Right (n=9)	Total (n=18)	Left (n=22)	Right (n=22)	Total (n=44)	
MTJ-ST	0.599	0.267	0.449	-0.143	-0.313	-0.224	0.085
MTJ-MKH	0.372	0.260	0.313	0.043	0.101	0.081	0.216
MTJ-IP	0.879	0.843	0.856	0.628	0.502	0.566	0.779

(IP: first interphalangeal joint, MKH: master knot of Henry, MTJ: musculotendinous junction, ST: sustentaculum tali)

CHAPTER V
DISCUSSIONS

Achilles tendinopathy is a painful condition that can happen in active and inactive people [50]. Patients generally have pain with first activity in the morning and increase with exercise. Over time, pain can develop at rest [34]. The surgical intervention might be necessary when the clinical outcome remains disappointing with noninvasive treatments [1, 3]. FHL tendon is commonly used in the augmentation of the Achilles tendon because it is easy to harvest and provide the good outcomes regardless of the technique used to harvest the tendon, including single posterior medial incision, double incision technique and minimally invasive technique [1, 34, 35].

5.1 Foot length

Foot consists of twenty-six bones, multiple layers of muscles, tendons and ligaments which ensure static and dynamic functions. The shape and morphology of the foot vary among ethnicities, genders, and individuals [51-55]. Foot length was used in this study to anticipate anatomical data which is significant for FHL tendon transfer, including MKH surface location and FHL tendon length. Asian foot length is shorter than that of North American and European. In Asian, the most frequent length was 255 mm for male and 235 mm for female [56]. The mean foot lengths of Thai elderly were 250 mm and 232 mm in male and female [57]. Moreover, the mean foot lengths in male and female were 248 mm and 216 mm in a Thai cadaveric study [58]. In this study, the mean foot lengths were 246 mm and 225 mm in male and female respectively. A significant difference between genders was found similar to previous reports.

5.2 Morphology and location of MTJ

In this study, only type 1 and 3 of FHL morphology according to the classification of Mao et al. were found [23]. The most frequency type was type 1 which was similar to the reports from Pichler et al. and Mao et al. (7, 23). Symmetrical type of MTJ morphology was found in a high prevalence (89.16% of cases). Awareness of symmetrical patterns should be emphasized. The location of medial and lateral muscle belly can be identified at proximal or distal to zero point similar to previous reports (7, 23). However, all MTJ of medial muscle belly was proximal to the zero point. This finding was differed from previous studies (Table 30) (7, 23). Knowledge of morphological variation of FHL muscle will provide a benefit in tendon harvesting and transfer. The length of the tendon graft obtained from the FHL tendon might be varied by the location of MTJ. Therefore, if FHL muscle bellies are adequate for the coverage of tendon defect and vascular supply to the affected area, other additional techniques will not be required. Consequently, these anatomical variations should be aware when interpreting the finding in MRI or ultrasound of this area (7, 23).

Table 30 Comparisons of MTJ type and distance from MTJ to measuring point **(7, 23)**

Author	Year	Race/Ethnic	Cadaveric type	n	MTJ morphology (n, %)			
					Type 1	Type 2	Type 3	Other
This study	2020	Thai	Fresh and	62				
• Prevalence			Embalmed	104	145 (87.3)	0 (0)	21 (12.7)	0 (0)
• Distance from MTJ to the crossing of distal osseous part of tibia and FHL tendon								
- Medial belly (mm)					-21.99±13.21			
- Lateral belly (mm)					5.83±11.64			
Mao et al. (23)	2018	Asian	embalmed	70				
• Prevalence					63 (90)	5 (7.1)	2 (2.9)	0 (0)
• Distance from MTJ to the crossing of distal osseous part of tibia and FHL tendon								
- Medial belly (mm)					33.24±1.5			
- Lateral belly (mm)					3.14±2.2			
Pichler et al. (7)	2005	-	embalmed	80				
• Prevalence					70 (88)	3 (4)	5 (6)	2 (3)
• Distance from MTJ to the bone cartilage transition of tibia								
- Medial belly (mm)					+114	+10	+32	-
- Lateral belly (mm)					+26	+10	+57	-

+: proximal to measuring point - : distal to measuring point (MTJ: musculotendinous junction)

5.3 Relationship between FHL tendon and NVB at ankle joint

At medial side of ankle joint, TNVB (tibial nerve, posterior tibial artery and veins) resided posterior or medial to FHL tendon. A detailed knowledge of this anatomical relation between them is important in order to avoid injury to the TNVB. The result of this study revealed no measurable distance between TNVB and FHL tendon in all specimens. This was dissimilar to the result from a previous cadaveric study reporting a mean distance of 3.46 ± 2.12 mm between FHL tendon and neurovascular bundle in 94.3% of specimens (23). In addition, one total ankle MRI study showed a mean distance of 1.3 mm (24). Taking together, TNVB is very close to FHL tendon and has a high risk to be injured (24).

5.4 Location of MKH

MKH has been widely utilized as a surgical landmark for the FHL tendon graft harvesting especially in double incision technique (14). MKH is used as a landmark during reconstruction procedures because even if one of FHL and FDL tendons is transferred beyond the level of MKH, the toes would still be function (59). The first IP joint and NT were used to localize MKH by Mao et al. in Asian embalmed cadavers (12). Moreover, Beger et al. and Vasudha et al. further investigated the precise location of the MKH from MM, NT and first IP joint in Turkish and Indian formalin fixed cadavers, respectively (14, 31). According to the results of this study, the location of MKH resided proximal to the first IP joint, inferior to NT and distal to MM which resembled findings of previous reports (Table 31) (14, 31). The result of previous research suggested that if the incision line was made distal to MKH, it would be better for obtaining the graft (12, 60, 61). With adequate knowledge of MKH location, a smaller skin incision can be performed during surgery which can also preserve the MPNVB, thereby decreasing the wound complication (30, 62).

Table 31 Comparisons of distances from MKH to MM, NT, and IP [12, 14, 31]

Authors	Year	Race/ Ethnic	Cadaveric type	n	Anatomical landmarks (cm) mean±SD (min-max)		
					MM	NT	IP
This study	2020	Thai	Soft	62	5.96±0.75 (3.46 –7.87)	2.63±0.48 (1.79 – 4.09)	11.71±1.00 (9.31 – 15.13)
Vasudha et al. [31]	2019	Indian	Formalin fixed				
left				36	6.07 ± 1.25 (4.03-9.00)	2.99 ±0.96 (1.50-5.50)	11.97± 1.11 (9.32-14.2)
right				36	6.10 ± 1.17 (4.26-8.50)	3.24±0.93 (1.64-5.00)	12.50 ±0.89 (9.77-14.46)
Beger et al. [14]	2018	Turkish	Formalin fixed	20	5.93± 0.74 (4.72-7.35)	1.75 ± 0.39 (1.11-2.44)	12.61 ± 1.11 (10.33-14.09)
Mao et al. [12]	2014	Asian	Embalmed	64	-	2.21± 0.34 (1.59–3.04)	10.89 ±1.08 (13.04–9.22)

(IP: first interphalangeal joint, NT: navicular tuberosity, MM: medial malleolus)

5.5 Surface location of MKH

Although there were several reports about the location of the MKH, they did not take surface landmarks for localizing MKH into account. Medial end of plantar flexion crease at the base of great toe (MC) and navicular tuberosity (NT), which could be clearly identified and palpated, were used to determine the surface localization of MKH in this study. For accuracy and easy application in clinical practice, MC-NT line and A which is the perpendicular point of MKH on MC-NT line were defined. The surface location of MKH is calculated into the percentage of the length of MC-T. Approximately, MKH located at 95% of MC-NT line from MC with a perpendicular distance of 25 mm from MC-NT line (Figure 69). The percentage of these lines did not have statistically significant differences between sides and genders. However, the results of this study revealed that point A could be located anterior, posterior and at the NT on MC-NT line. Nevertheless, MKH was located posterior to NT in only 6.5 % of cases.

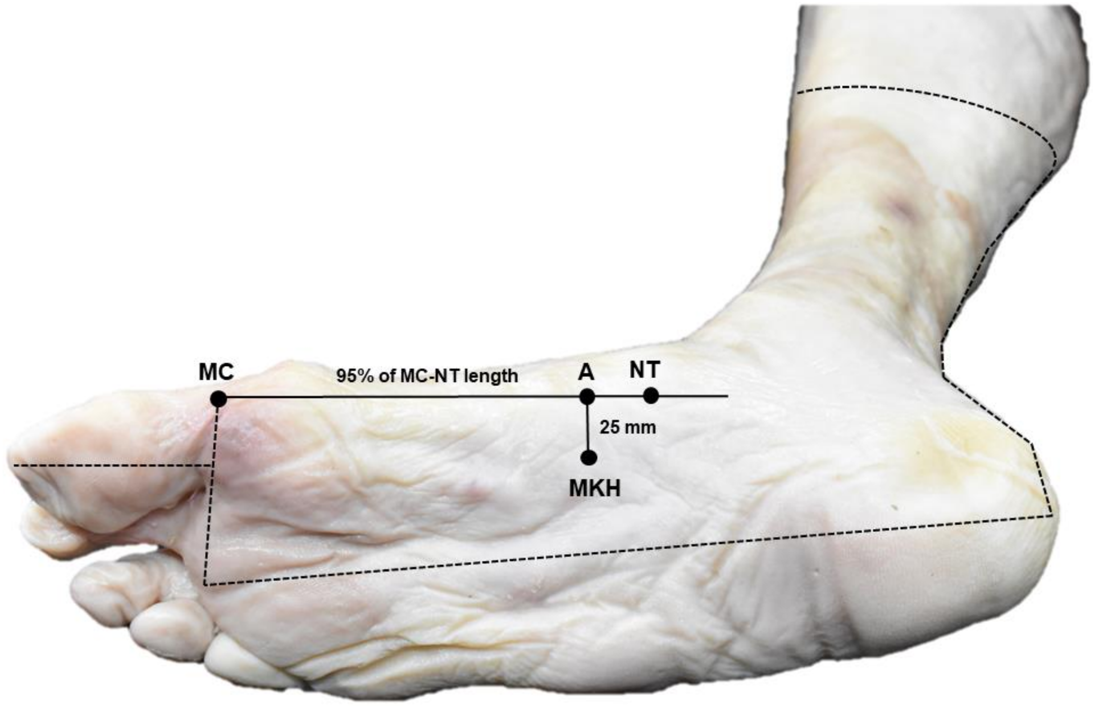


Figure 69 Photographs of plantar surface (right ankle and foot) showing the surface location of MKH on MC-NT line

(A: perpendicular point of MKH on MC-NT line, MC: medial end of plantar flexion crease at the base of the great toe, MKH: master knot of Henry, NT: navicular tuberosity)

5.6 Relationship of MKH and neurovascular bundle

MPN and LPN are the branches of posterior tibial nerve which supply skin and intrinsic muscle of sole. Anatomically, MPN travels along the plantar surface of FDL tendon and passes through MKH [(15)]. LPN obliquely passes forward between FDB and quadratus plantae to lateral side of the foot. The anatomical relationship between the plantar nerves and MKH was reported by Mao and colleague in embalmed cadavers [(16)]. They found a mean distance of 5.26 mm between MPN and MKH, and 15.50 mm between LPN and MKH which was different from the result of this study. In all specimens of this study, there was no distance between MPNVB and MKH and a longer distance of 17.13±3.55 mm was observed between LPNVB and MKH. This might be due to the different methods of cadaveric fixation. In embalmed cadaver, most tissues of cadavers are rigid and joints cannot be moved freely which may affect the location of anatomical structure [63]. The proximity of MKH and MPNVB might lead to neurovascular injury. The injuries of the distal branches of the posterior tibial nerve and artery were reported previously [12, 16]. The transection of tendon that was performed near MKH in double incision technique may cause MPN or LPN injury [12]. In the literature, it was hypothesized that difficult harvesting may be the cause of nerve injury [15]. Thus, caution is required to preserve this neurovascular bundle especially when distal transection performed blindly [36, 42]. Moreover, tendon disease in the region of MKH may lead to the entrapment of MPN [20].

5.7 Tendinous interconnection between FHL and FDL tendon

FHL tendon is routinely used in reconstructive foot and ankle surgery. The exact knowledge of their anatomy and variation is important for harvesting and calculating the functional loss after transposition [31]. In addition, it is important to aware the number of connections between tendons while harvesting tendon grafts distal to MKH [14]. Comprehensive classification according to Beger et al. was applied in this study and the result showed the existence of connection between FHL and FDL tendons in all specimens. Among the types of connection, type I is the majority of cases in the present study which is similar to those previous studies (Table 32) [10, 12, 15, 25, 27-31]. No case of type III, IV, VI and VII was identified in the present study. In terms of overall proportions, this finding was resembled to the result of Edama et al. in Asian cadavers [25]. In other ethnic studies, the presenting of type III, IV, VI and VII were varied from 0-30%. Therefore, it suggested that ethnic differences might exist. In this study, there was a new type of tendinous interconnection which has not been reported previously. FHL tendon bifurcated into two tendons, one tendon inserted to the first toe and the other tendon fused with FDL tendon. From the anatomical observation, FHL might affect the movement of all toes in this type of connection. In the previous reports, Hur et al. and Vasudha et al. reported the different unusual type which had fibers from flexor digitorum accessories (FDA) to the long flexor tendons of the toe (31, 33). Vasudha et al. suggested that, there were the contribution of FDA to the toes flexor tendons (31). Tendinous interconnection between FHL and FDL tendon provided clinical benefit. If one of FHL or FDL tendon is transferred beyond the level of MKH, the toes will still function without impairment (7, 59). The tendinous slips from FHL propose the stable base for toe-off movements (33). Thus, types of interconnections play a crucial role in defining the level of functional gain of toe movement in the postoperative period (31). Moreover, the length of the graft can be increased by including the tendinous interconnection into the graft in all types of communications except type IV (31).

Table 32 Comparisons of the prevalence types of tendinous interconnection between FHL and FDL tendons (classification according to Beger et al.) (10, 12, 14, 15, 25, 27-31)

Author	Year	Race / Ethnic	Cadaveric type	n	%							
					Type I	Type II	Type III	Type IV	Type V	Type VI	Type VII	Other
This study	2020	Thai	Embalmed Soft	102 62	82.6	0.6	0	0	7.9	0	0	8.5
Vasudha et al. (31)	2019	Indian	Formalin fixed	36	61	2.94	7.35	14.70	8.82	0	1.47	2.94
Beger et al. (14)	2018	Turkish	Formalin fixed	20	75	10	0	0	5	5	5	-
Edama et al. (25)	2016	Asian	Formalin fixed and alcohol	100	86	3	0	0	11	0	0	-
Mao et al. (12)	2015	Asian	Embalmed	64	96.9	3.1	0	0	-	-	-	-
Plaass et al. (30)	2013	Caucasian	Embalmed	60	67	3	30	0	-	-	-	-
Mulier et al. (15)	2007	-	Fresh Embalmed	20 4	58	29	0	13	-	-	-	-
LaRue et al. (29)	2006	Caucasian	Fresh Embalmed	5 19	42	41	0	17	-	-	-	-
O'Sullivan et al. (10)	2005	-	Embalmed	16	68	13	19	0	-	-	-	-
Wapner et al. (28)	1994	-	Embalmed	85	67	31	-	2	-	-	-	-
Martin (27)	1964	-	Embalmed	33	88	6	0	6	-	-	-	-

5.8 Location of tendinous interconnection between FHL and FDL tendon

Tendinous interconnections between FHL and FDL tendon might restrict the harvesting of the FHL tendon distal to MKH [13]. Therefore, their locations are important to be investigated. The anatomical landmarks including MM, NT, IP, MKH and FDL tendon division were used to locate the interconnection between FHL and FDL tendons in previous studies [14, 30, 32]. MKH was selected as the reference landmark in this study because these interconnections must be cut with an additional incision by medial or direct plantar approach in minimally invasive technique of FHL tendon harvesting and transfer. Moreover, Mao et al. proposed that the incision line should start from MKH [12]. The result of this study reveal that tendinous interconnection located either proximal (-) or distal (+) to MKH. However, the mean distance from tendinous interconnection to MKH was positive. The tendinous slip from FHL to FDL and that from FDL to FHL tendon was located at 1 mm and 13 mm distal to MKH, respectively. Dissimilar to this result, the tendinous slips placed distal to MKH and proximal to FDL tendon division in the study of Beger et al. and Oddy et al. [14, 32]. Beger et al. suggested that, the interconnection from FHL to FDL could be cut at an average of 27.1 mm distal to the MKH and that from FDL to FHL could be cut at an average of 27.1 mm proximal to FDL tendon division [14]. The difference between studies may be due to the number of specimens, method of cadaveric preservation and ethnicity.

5.9 Distribution of tendinous slip

In this study, type of distribution of tendinous slip to lesser toes was determined by the method of Plaass et al. [30]. Determination of the types of distribution by observation of movement of FDL and FHL tendons while moving each toe demonstrated four types, including a, b, c, and d. Type b was the most frequent finding which was similar to previous reports (Table 33) [12, 14, 25, 28, 30, 33]. Considering the branching type, the FHL was presumed to not only act as the great toe flexor, but also play a significant role in the flexion of second and third toes [12, 25].

Table 33 Comparison of prevalence of type of the slip distribution to the lesser toes **(12, 14, 25, 28, 30, 33)**

Author	Year	Race / Ethnic	Cadaveric type	n	Type a (%)	Type b (%)	Type c (%)	Type d (%)
This study	2020	Thai	Soft and Embalmed	164	19.5	67.7	11.0	1.8
Beger et al., [14]	2016	Turkish	Formalin fixed	20	33	55	7	0
Edama et al., [25]	2016	Asian	Formalin fixed and alcohol	100	31	61	8	0
Mao et al., [12]	2015	Asian	Embalmed	64	31	61	8	0
Plaass et al., [30]	2013	Caucasian	Embalmed	60	67	3	30	0
Hur et al., [33]	2011	Korean	Embalmed	100	8	64	28	0
Wapner et al., [28]	1994	-	Embalmed	85	41	47	9	-
LeDouble [28]	1897	-	-	-	32	58	10	0
Testut [14]	1884	-	-	-	22	40	36	2

5.9 Width of tendinous interconnection

The tendinous interconnection between the FHL and FDL is surmised to exert a flexion action on the lesser toes, but it was quantified in one report [25]. Edama et al. proposed that, flexion action of FHL on the lesser toes might be estimated by calculating the cross sectional areas (CSAs) of FHL branches to the lesser toes with Image analysis software. In their study, the proportion of FHL with respect to flexor tendons of lesser toes was diverse from 5-73%. The proportion of FHL to 2nd and 3rd toes was higher, approximately 50–70%. In this study, the width of tendinous slip was used to quantify the flexion action on the lesser toes. Width of tendinous slip can be easily measured in clinical setting. The mean width of proximal and distal tendinous interconnections was about 3.70 and 2.90 mm, respectively. Nevertheless, correlation between width of slip and type of slip distribution to lesser toes was not found.

5.10 Length of FHL tendon graft

In this study, the length of tendon graft with three different incision techniques (single incision technique, double incision technique and minimally invasive technique) was quantified. Previous researches reported that the in situ length of harvested FHL tendon were different between techniques (Table 34) [12, 14, 36]. Different techniques of measurement and results were observed between the cadaveric studies [12, 14, 36]. The technique of measurement in this study was similar Mao et al and Beger et al., but the result was different [12, 14]. The length of tendon graft from single incision technique in this study was shorter than previous studies. In double incision technique, our result was longer when compared to those of Mao et al. and Beger et al., but shorter than that of Tashjian et al. Furthermore, the length of tendon graft from minimally invasive technique was found to be longer when compares with Moa et al. Nevertheless, it was shorter than the mean length from the study of Beger et al. [14]. These differences might be caused by the different ethnic backgrounds, cadaveric preservation technique and position of foot and ankle during measurement.

Table 34 Comparisons of harvested FHL tendon length in cadaveric studies [12, 14, 36]

Authors	Year	Ethnic	n	Cadaveric type	Tendon length (cm) mean± SD (range)		
					Single incision technique	Double incision technique	Minimally invasive technique
This study	2019	Thai	62	Soft	3.90±1.09 (1.50 – 7.10)	7.34±0.99 (5.40 – 9.50)	19.80±1.39 (17.40 – 24.00)
Beger et al., [14]	2018	Turkish	20	Formalin fixed	5.75± 0.63 (4.52–6.86)	7.03± 0.86 (5.77–8.80)	20.22± 1.32 (16.82–21.97)
Mao et al., [12]	2015	Asian	64	Embalmed	5.08± 1.09 (3.32–10.35)	6.72± 1.02 (4.69–12.09)	17.49± 1.80 (13.51–20.52)
Tashjian et al., [36]	2003	US	14	Fresh frozen	5.16± 1.29 (3.4–6.9)	8.09± 1.63 (5.1–11.1)	-

Ex vivo length of tendon graft has never been reported previously. Ex vivo length refers to the length of tendon after it is cut from the insertion point, which may be more similar to the length of harvested tendon for transfer. Our results revealed significant differences between in situ and ex vivo length of tendon from all techniques. Ex vivo tendon length was shorter than in situ tendon length by about 4.5 mm in single incision and double incision techniques and 6.0 mm in minimally invasive technique. The shorter tendon might result from loss of tension after it was cut from the insertion site in the foot. The correlation between tendon length and foot length was analyzed for clinical benefit. Our results showed a moderate positive correlation between them. The lengths of harvested tendon from single incision, double incision and minimally invasive technique were about 15%, 30%, and 85% of foot length, respectively. Thus, it might be possible to estimate the length of harvested tendon from the foot length.

CHAPTER VI
CONCLUSIONS

This study provided the morphological and morphometric data which related to FHL tendon harvesting and transfer as follows:

1. The mean foot lengths were 246 mm in male and 225 mm in female with a significant difference between genders which was similar to previous reports.
2. Two types of MTJ morphology according to Mao et al., were identified which were type 1 and type 3 [23]. Most specimens had the longer lateral muscle belly than medial muscle belly (type 1) and symmetrical type of MTJ morphology was found in 89.16%. Lateral muscle belly was distal to zero point while medial muscle belly was proximal to zero point. Morphology and location of MTJ played an important role in harvesting length of the tendon graft and the effectiveness of tendon transfer.
3. MKH resides distal to MM, under NT and proximal to IP. Surface localization of MKH can be located at 95% of MC-NT line from MC with a perpendicular distance of 25 mm from MC-NT line. This precise surface location of MKH will be useful for the identification of incision site and surgical improvement.
4. The close relationship was found between FHL and neurovascular bundle at the ankle joint and between MKH and MPNVB at plantar surface of foot. Knowledge of the relation between these anatomical structures and neurovascular bundle will assist the clinician to avoid iatrogenic injury.
5. Four types of tendinous interconnection between FHL and FDL tendon according to Beger et al. were defined. Most specimens were type I (a slip

directly from FHL to FDL tendon) and symmetrical type of tendinous interconnection was found in 79.27%. A new type in which FHL tendon bifurcated into one tendon to the great toe and the other tendon fused with FDL tendon was reported in this study. The mean distance of proximal and distal tendinous slips was 1 mm and 13 mm distal to MKH, respectively. Thus, to cut the tendinous interconnection, the incision line could be longer to 13 mm distal to MKH.

6. Four types of slip distribution to lesser toes according to Plaass et al., including type a, b, c, and d, were identified in this study [30]. Type b with a distribution to 2nd and 3rd, was the majority. FHL was presumed to play a role in 2nd and 3rd toes flexion.
7. The ex vivo lengths of tendon graft in all techniques were significantly shorter than in situ length. The in situ and ex vivo length of FHL tendon from minimally invasive technique was longest and it was 83% and 85% of foot length, respectively. Moreover, it had the moderate positive correlation to foot length. Knowledge of the approximate FHL tendon length could be used by the surgeon in personalizes designing the appropriate operation technique for individual patient.
8. Foot length, MKH-IP, MKH-NT, MC-NT, MC-A, MKH-A and FHL tendon lengths from minimally invasive technique had statistically significant differences between genders.

APPENDIX

Statistical analysis

1. Foot length

The comparison between sides

Parameter	Gender	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
Foot length	Male	18	22.5	27.0	24.65	1.20	0.165	0.278	0.937	-
	Female	44	20.0	25.0	22.46	1.16	0.200	0.688	0.026	-

The comparison between genders

Parameter	Sides	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U test
Foot length	Left	31	20.0	26.8	23.03	1.60	0.200	0.963	0.000	-
	Right	31	20.3	27.0	23.16	1.50	0.200	0.754	0.000	-

2. Location of MTJ

The comparison between sides

Parameter	Gender	n	Distance (mm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
Lateral belly	Male	18	-8.39	21.21	8.77	9.63	0.200	0.096	0.804	-
	Female	44	-30.62	20.96	4.63	12.26	0.001	0.001	-	0.322
Medial belly	Male	14	-42.12	-12.08	-24.79	9.66	0.200	0.416	0.690	-
	Female	43	-65.95	-4.93	-21.08	14.16	0.005	0.000	-	0.394

The comparison between genders

Parameter	Sides	n	Distance (mm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U test
Lateral belly	Left	31	-18.27	20.96	5.58	11.26	0.005	0.020	-	0.260
	Right	31	-30.62	21.21	6.43	12.18	0.002	0.003	-	0.514
Medial belly	Left	30	-51.02	-4.93	-23.63	13.21	0.199	0.088	0.383	-
	Right	27	-65.95	-5.54	-20.16	13.22	0.013	0.000	-	0.243

3. MKH location

The comparison between sides

Parameter	Gender	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
MKH-IP	Male	18	106.56	151.27	125.54	10.55	0.200	0.788	0.623	-
	Female	44	93.14	129.50	113.66	7.47	0.200	0.663	0.628	-
MKH-NT	Male	18	19.53	40.91	28.66	5.68	0.200	0.629	0.495	-
	Female	44	17.93	35.87	25.31	3.99	0.200	0.280	0.134	-
MKH-MM	Male	18	34.59	78.71	61.67	10.26	0.068	0.068	0.497	-
	Female	44	44.43	78.07	58.72	6.00	0.200	0.132	0.062	-

The comparison between genders

Parameter	Sides	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U test
MKH-IP	Left	31	93.14	137.88	116.60	9.77	0.200	0.985	0.002	-
	Right	31	100.2	151.27	117.62	10.36	0.126	0.031	-	0.004
MKH-NT	Left	31	17.93	40.91	27.15	4.92	0.093	0.145	0.220	-
	Right	31	18.30	35.87	25.41	4.50	0.200	0.953	0.048	-
MKH-MM	Left	31	47.02	78.71	61.21	7.54	0.007	0.038	-	0.338
	Right	31	34.59	75.27	57.95	7.23	0.157	0.927	0.315	-

4. MKH surface landmark

The comparison between sides

Parameter	Gender	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
MC-NT	Male	18	91.75	124.12	113.12	8.67	0.010	0.072	0.995	-
	Female	44	87.18	117.65	105.01	7.46	0.200	0.262	0.006	-
MKH-A	Male	18	19.39	41.85	28.49	6.94	0.081	0.134	0.708	-
	Female	22	16.89	34.15	23.72	3.88	0.177	0.227	0.213	-
MC-A	Male	9	87.26	139.77	111.23	12.99	0.200	0.863	0.881	-
	Female	22	76.05	116.74	97.83	9.21	0.200	0.753	0.074	-

The comparison between genders

Parameter	Sides	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U test
MC-NT	Left	31	87.18	124.12	105.63	9.86	0.200	0.745	0.005	-
	Right	31	97.26	122.19	109.10	6.85	0.012	0.122	0.034	-
MKH-A	Left	31	17.26	41.85	25.61	5.80	0.017	0.000	-	0.655
	Right	31	16.89	35.53	24.60	4.93	0.200	0.136	0.015	-
MC-A	Left	31	76.05	126.71	100.47	12.75	0.200	0.881	0.426	-
	Right	31	86.91	139.77	102.98	11.30	0.136	0.027	-	0.024

5. Location of MKH in term of percentage of MC-NT line

The comparison between sides

Parameter	Gender	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
MC-NT	Male	18	82.21	137.72	98.59	11.98	0.000	0.001	-	0.327
	Female	44	75.82	107.16	93.18	5.95	0.087	0.093	0.616	-

The comparison between genders

Parameter	Sides	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U test
MC-NT	Left	31	75.83	110.28	95.03	6.96	0.122	0.232	0.050	-
	Right	31	79.82	137.72	94.47	9.80	0.000	0.000	-	0.537

6. Distance between MKH and neurovascular bundles

The comparison between sides

Parameter	Gender	n	Distance (mm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
MKH-LPNVB	Male	18	9.59	30.29	18.95	5.64	0.200	0.358	0.512	-
	Female	44	7.11	24.38	16.39	3.86	0.200	0.630	0.024	-

The comparison between genders

Parameter	Sides	n	Distance (mm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U test
MKH-LPNVB	Left	31	8.44	30.29	15.99	4.68	0.200	0.225	0.131	-
	Right	31	7.11	28.85	18.28	4.19	0.073	0.465	0.168	-

7. Location of tendinous interconnection

The comparison between sides

Parameter	Gender	n	Distance (mm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
Type I	Male	13	-59.47	14.96	-3.32	24.29	0.000	0.000	-	0.345
	Female	33	-21.33	18.65	1.68	10.17	0.092	0.491	0.923	-
Type V - proximal slip	Male	2	0.00	9.00	4.50	6.36	-	-	-	-
	Female	3	4.59	12.47	8.02	4.04	-	0.584	-	-
-Distal slip	Male	2	14.07	14.44	14.25	0.26	-	-	-	-
	Female	3	7.05	16.13	12.08	4.62	-	0.649	-	-
Other	Male	3	-20.81	17.56	-4.10	19.66	-	0.581	-	-
	Female	8	-11.36	20.52	2.87	10.91	0.200	0.703	0.704	-
All type - proximal slip	Male	18	-59.47	17.56	-2.58	21.71	0.000	0.000	-	0.441
	Female	44	-21.33	20.52	2.33	9.99	0.173	0.483	0.431	-
-Distal slip	Male	2	14.07	14.44	14.25	0.26	2	14.07	-	-
	Female	3	7.05	16.13	12.08	4.62	3	7.05	-	-

The comparison between genders

Parameter	Gender	n	Distance (mm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U Test
Type I	Left	23	-54.39	18.06	1.07	15.61	0.090	0.000	-	0.726
	Right	23	-59.47	18.65	-0.53	15.43	0.000	0.000	-	0.892
Type V - proximal slip	Left	3	0.00	12.47	7.15	6.43	-	0.521	0.439	-
	Right	2	4.59	7.02	5.80	1.72			-	
-Distal slip	Left	3	14.07	16.13	14.88	1.10	-	0.319	0.106	-
	Right	2	7.05	13.05	10.05	4.24	-	-	-	-
Other	Left	5	-9.04	13.52	3.03	8.30	0.200	0.847	0.094	-
	Right	6	-20.81	20.52	-0.750	16.71	0.200	0.424	0.939	-
All type - proximal slip	Left	31	-54.39	18.06	1.97	13.93	0.008	0.000	-	0.777
	Right	31	-59.47	20.52	-0.16	14.96	0.001	0.000	-	0.982
-Distal slip	Left	3	14.07	16.13	14.88	1.10	-	0.319	0.106	-
	Right	2	7.05	13.05	10.05	4.24	-	-	-	-

8. Width of tendinous interconnection

The comparison between sides

Parameter	Gender	n	Width (mm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
Type I	Male	13	2.15	6.02	3.75	0.97	0.101	0.301	0.509	-
	Female	32	2.15	7.76	3.79	1.20	0.110	0.006	-	0.594
Type V - proximal slip	Male	2	1.94	2.73	2.33	0.56	-	-	-	-
	Female	3	1.58	2.32	1.86	0.40	-	0.213	-	-
-Distal slip	Male	2	2.96	3.12	3.04	0.11	-	-	-	-
	Female	3	2.32	3.11	2.58	0.46	-	0.000	-	-
Other	Male	3	3.15	4.96	4.12	0.91	-	0.773	-	-
	Female	8	3.51	4.99	4.12	0.48	0.200	0.827	0.041	-
All type - proximal slip	Male	18	1.94	6.02	3.65	1.02	0.200	0.583	0.467	-
	Female	43	1.58	7.76	3.72	1.17	0.200	0.046	-	0.520
-Distal slip	Male	2	2.96	3.12	3.04	0.11	-	-	-	-
	Female	3	2.32	3.11	2.58	0.46	-	0.000	-	-

The comparison between genders

Parameter	Gender	n	Width (mm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U Test
Type I	Left	23	2.15	5.57	3.63	0.88	0.200	0.889	0.996	-
	Right	22	2.15	7.76	3.94	1.33	0.141	0.018	-	0.944
Type V - proximal slip	Left	3	1.94	2.73	2.33	0.39	-	0.958	0.986	-
	Right	2	1.58	1.67	1.62	0.06	-	-	-	-
-Distal slip	Left	3	2.32	3.12	2.80	0.42	-	0.363	0.121	-
	Right	2	2.32	3.11	2.71	0.56	-	-	-	-
Other	Left	5	3.51	4.96	4.07	0.61	0.200	0.347	0.099	-
	Right	6	3.15	4.99	4.15	0.59	0.099	0.311	0.206	-
All type - proximal slip	Left	31	1.94	5.57	3.58	0.91	0.200	0.899	0.739	-
	Right	30	1.58	7.76	3.83	1.31	0.083	0.071	0.976	-
-Distal slip	Left	3	2.32	3.12	2.80	0.42	-	0.363	0.121	-
	Right	2	2.32	3.11	2.71	0.56	-	-	-	-

9. In-situ tendon length

The comparison between sides

Parameter	Gender	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
MTJ-ST	Male	18	2.10	6.00	4.24	1.01	0.200	0.790	0.131	-
	Female	44	1.50	7.10	3.77	1.10	0.004	0.110	0.601	-
MTJ-MKH	Male	18	6.00	9.50	7.63	0.96	0.168	0.382	0.812	-
	Female	44	5.40	9.50	7.23	0.99	0.200	0.628	0.191	-
MTJ-IP	Male	18	18.10	24.00	20.95	1.60	0.105	0.347	0.949	-
	Female	44	17.40	21.50	19.33	0.97	0.140	0.155	0.279	-

The comparison between genders

Parameter	Sides	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U test
MTJ-ST	Left	31	1.50	6.20	3.92	1.09	0.013	0.244	0.106	-
	Right	31	1.90	7.10	3.89	1.11	0.200	0.296	0.408	-
MTJ-MKH	Left	31	5.90	9.50	7.27	0.88	0.153	0.128	0.097	-
	Right	31	5.40	9.50	7.42	1.10	0.200	0.644	0.624	-
MTJ-IP	Left	31	17.40	24.00	19.72	1.43	0.041	0.073	0.001	-
	Right	31	17.90	24.00	19.87	1.37	0.200	0.041	-	0.017

10. Ex-vivo tendon length

The comparison between sides

Parameter	Gender	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
MTJ-ST	Male	18	1.90	5.00	3.75	0.87	0.200	0.469	0.532	-
	Female	44	1.10	5.80	3.32	1.06	0.111	0.488	0.861	-
MTJ-MKH	Male	18	5.70	9.00	7.11	0.89	0.145	0.191	0.760	-
	Female	44	5.10	8.90	6.76	0.96	0.141	0.195	0.256	-
MTJ-IP	Male	18	17.40	23.60	20.37	1.65	0.200	0.496	0.912	-
	Female	44	16.70	20.90	18.69	0.94	0.200	0.916	0.456	-

The comparison between genders

Parameter	Sides	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U test
MTJ-ST	Left	31	1.10	5.70	3.45	1.06	0.089	0.284	0.210	-
	Right	31	1.50	5.80	3.43	0.10	0.200	0.954	0.412	-
MTJ-MKH	Left	31	5.40	9.00	6.79	1.00	0.053	0.074	0.144	-
	Right	31	5.10	8.70	6.93	1.00	0.173	0.285	0.688	-
MTJ-IP	Left	31	16.70	23.60	19.13	1.47	0.200	0.130	0.002	-
	Right	31	17.30	23.50	19.22	1.35	0.200	0.056	0.001	-

11. The comparison between in-situ and ex-vivo tendon length

Parameter	Techniques	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
MTJ-ST	In-situ	62	1.50	7.10	3.90	1.01	0.015	0.524	-	0.000
	Ex-vivo	62	1.10	5.80	3.44	1.02	0.986	0.701		
MTJ-MKH	In-situ	62	5.40	9.50	7.34	0.99	0.094	0.335	0.000	
	Ex-vivo	62	5.10	9.00	6.86	0.94	0.973	0.189		
MTJ-IP	In-situ	62	17.40	24.00	19.79	1.39	0.009	0.004	-	0.000
	Ex-vivo	62	16.70	23.60	19.18	1.40	0.943	0.006		

12. Different length between in-situ and ex-vivo tendon length

The comparison between sides

Parameter	Gender	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
MTJ-ST	Male	18	0.20	1.00	0.49	0.26	0.043	0.017	-	0.932
	Female	44	0.00	1.30	0.45	0.23	0.005	0.001	-	0.749
MTJ-MKH	Male	18	0.30	1.00	0.52	0.18	0.025	0.033	-	0.523
	Female	44	0.00	1.10	0.47	0.22	0.000	0.016	-	0.766
MTJ-IP	Male	18	0.30	1.00	0.58	0.22	0.048	0.067	0.915	-
	Female	44	0.20	1.60	0.63	0.32	0.000	0.001	-	0.261

The comparison between genders

Parameter	Sides	n	Length (cm)				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U test
MTJ-ST	Left	31	0.10	1.00	0.46	0.23	0.014	0.021	-	0.774
	Right	31	0.00	1.30	0.46	0.25	0.000	0.001	-	0.894
MTJ-MKH	Left	31	0.10	1.00	0.47	0.21	0.058	0.139	0.502	
	Right	31	0.00	0.10	0.49	0.21	0.000	0.003	-	0.461
MTJ-IP	Left	31	0.20	1.30	0.59	0.23	0.005	0.052	0.979	
	Right	31	0.30	1.60	0.65	0.35	0.001	0.002	-	0.685

13. In situ length of harvested FHL tendon in term of percentage of the foot length

The comparison between sides

Parameter	Gender	n	%				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
MTJ-ST	Male	18	9.33	24.29	17.14	3.90	0.200	0.980	0.513	-
	Female	44	6.38	33.81	16.88	5.21	0.160	0.080	0.929	-
MTJ-MKH	Male	18	26.15	36.93	30.97	3.79	0.074	0.023	-	0.859
	Female	44	23.40	45.24	32.26	4.65	0.200	0.815	0.312	-
MTJ-IP	Male	18	78.75	93.36	84.93	3.78	0.200	0.963	0.928	-
	Female	44	75.74	93.75	85.92	3.67	0.200	0.972	0.213	-

The comparison between genders

Parameter	Sides	n	%				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U test
MTJ-ST	Left	31	6.38	28.84	17.02	4.63	0.150	0.455	0.745	-
	Right	31	8.19	33.81	16.90	5.11	0.200	0.047	-	1.000
MTJ-MKH	Left	31	25.11	39.07	31.63	3.78	0.200	0.365	0.677	-
	Right	31	23.40	45.24	32.14	5.04	0.200	0.618	0.338	-
MTJ-IP	Left	31	75.74	92.09	85.69	3.88	0.200	0.628	0.471	-
	Right	31	79.91	93.75	85.58	3.58	0.200	0.193	0.555	-

14. Ex-vivo length of harvested FHL tendon in term of percentage of the foot length

The comparison between sides

Parameter	Gender	n	%				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Wilcoxon Signed Ranks Test
MTJ-ST	Male	18	8.44	20.24	15.17	3.33	0.200	0.667	0.558	-
	Female	44	4.78	27.62	14.87	497	0.200	0.565	0.927	-
MTJ-MKH	Male	18	24.23	34.80	28.84	3.41	0.033	0.034	-	0.674
	Female	44	23.18	40.00	32.26	4.65	0.200	0.296	0.356	-
MTJ-IP	Male	18	74.58	89.21	82.55	3.84	0.200	0.783	0.895	-
	Female	44	74.89	94.76	83.31	3.95	0.200	0.532	0.846	-

The comparison between genders

Parameter	Sides	n	%				Test of normality		Statistical test	
			Min	Max	Mean	SD	Kolmogorov-Smirnov	Shapiro-Wilk	T-test	Mann-Whitney U test
MTJ-ST	Left	31	4.78	26.51	15.01	4.57	0.085	0.592	0.727	-
	Right	31	6.47	27.62	14.89	4.57	0.200	0.608	0.982	-
MTJ-MKH	Left	31	23.20	37.21	29.27	3.82	0.114	0.239	0.660	-
	Right	31	23.18	40.00	29.99	4.52	0.200	0.322	0.275	-
MTJ-IP	Left	31	74.58	90.23	83.12	3.89	0.200	0.599	0.568	-
	Right	31	75.98	94.76	83.06	3.98	0.200	0.077	0.694	-

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