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Anatomy of Master Knot of Henry: A morphometric study on cadavers

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ABSTRACT

Objective: The objective of this study was to evaluate the features of flexor hallucis longus (FHL), flexor digitorum longus (FDL) and flexor digitorum accessorius (FDA) muscles with relevance to the tendon grafts and to reveal the location of Master Knot of Henry (MKH).

Methods: Twenty feet from ten formalin fixed cadavers were dissected, which were in the inventory of Anatomy Department of Medicine Faculty, Mersin University. The location of MKH was identified. Interconnections of FHL and FDL were categorized. According to incision techniques, lengths of FHL and FDL tendon grafts were measured. Attachment sites of FDA were assessed.

Results: MKH was 12.61 ± 1.11 cm proximal to first interphalangeal joint, 1.75 ± 0.39 cm below to navicular tuberosity and 5.93 ± 0.74 cm distal to medial malleolus. The connections of FHL and FDL were classified in 7 types. Tendon graft lengths of FDL according to medial and plantar approaches were 6.14 ± 0.60 cm and 9.37 ± 0.77 cm, respectively. Tendon graft lengths of FHL according to single, double and minimal invasive incision techniques were 5.75 ± 0.63 cm, 7.03 ± 0.86 cm and 20.22 ± 1.32 cm, respectively. FDA was found to be inserting to FHL slips in all cases and it inserted to various surfaces of FDL.

Conclusion: The exact location of MKH and slips was determined. Two new connections not recorded in literature were found. It was observed that the main attachment site of FDA was the FHL slips. The surgical awareness of connections between the FHL, FDL and FDA, which participated in the formation of long flexor tendons of toes, could be important for reducing possible loss of function after tendon transfers postoperatively.

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Introduction

The term, “Master Knot by Henry, or equivalently used Henry’s Knot” was first identified as referring to the intersection territory, where the tendon of flexor digitorum longus (FDL) crosses over the tendon of flexor hallucis longus (FHL).^{1,2} Despite Master Knot of Henry (MKH) has been widely used as a surgical landmark during the tendon graft harvesting,^{2–5} awareness of exact anatomical settlement of this important area remains controversial.⁶ From this perspective, there is an intense need for further studies understanding the precise location of the MKH.

Tendon grafts of FHL and FDL are commonly used in reconstructive foot and ankle surgery.^{3,7–13} Despite the literature offers the descriptions of several techniques for harvesting these tendon grafts,^{2–6,14–16} there is a limited data based on the tendon graft lengths.⁶ Connections between FHL and FDL tendons is utmost important for harvesting tendon grafts.⁸ Knowledge of the interconnections is crucial for surgeons to minimize the functional loss during post-op period and understand the underlying cause of functional loss of toes.⁸ However, anatomical outcomes of these studies considering the interconnections harbor inconsistencies.^{6,8,17–21} In this regard, further studies on different

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populations can be of great help to clarify the anatomical inconsistency of these interconnections. Within the context of tendon grafting, another significant anatomical focus should be on the flexor digitorum accessorius (FDA) which acts directly on the flexor function of the toes considering its direct attachment to the tendons of FHL and FDL.^{22–24} Overall, a deeper view of the attachment of FDA both with FDL and FHL tendons is needed to a better understanding of the functional and anatomical properties of long flexor tendons of toes.

In summary, the main objectives of this study were to (1) determine the location of MKH, (2) measure the length of tendon grafts based on certain surgical techniques, (3) investigate the connections between the FHL and FDL and (4) define the attachment patterns of FDA.

Material and methods

The authors declare that they perform the study in accordance with the provisions of the Declaration of Helsinki 1995 (as revised in Edinburgh 2000). Twenty feet of 10 (2 females, 8 male) formalin-fixed adult cadavers in Turkish population were dissected (aged between 45 and 104 years, average 66.9 ± 18.9), which were in the inventory of Anatomy Department of Medicine Faculty, Mersin University. There were no signs of previous surgery or any other deformity around the ankle and foot. To expose the connections in the area of MKH, anatomic structures (skin, superficial fascia, plantar aponeurosis, flexor digitorum brevis and

abductor hallucis muscles) were removed and neurovascular bundles (posterior tibial artery, tibial nerve, medial and lateral plantar arteries and nerves) were retracted laterally. As follows, the concordant with their courses the mentioned tendons were dissected from musculotendinous junctions proximally towards the distal end of toes.

MKH was considered as the point where FDL crossed the FHL (Fig. 1). The distance of proximal and distal points of slips and MKH to medial malleolus, navicular tuberosity and first interphalangeal joint were recorded (Fig. 1a). FHL and FDL tendons were cut into two as proximal and distal parts at the MKH. Length, width and thickness of the proximal and distal parts of FHL and FDL plus the slips were measured. Relations of proximal and distal points of slips with MKH and FDL tendon division were evaluated.

Taking into account the study of Mao et al,⁶ tendon graft lengths of FHL harvested by single, double and minimal invasive incision techniques were measured (Fig. 2a). On the other hand, according to the parameters of Panchbhavi et al,^{15,16} the location of FDL tendon division and FDL tendon graft lengths harvested by plantar approach (Figs. 1b and 2b) were determined. Also, to find incision length and FDL tendon graft lengths in medial approach, the landmarks of Park et al⁴ were used (Fig. 2b). Distance from tip of second toe to back of heel was measured. Considering the previous studies,^{6,8,17,21} connections between FHL and FDL (Fig. 3) and the contribution of FHL slips to long flexor tendons of toes (Fig. 4) were classified. Connections of FDA with FHL and FDL were identified and innervation pattern of FDA was evaluated.

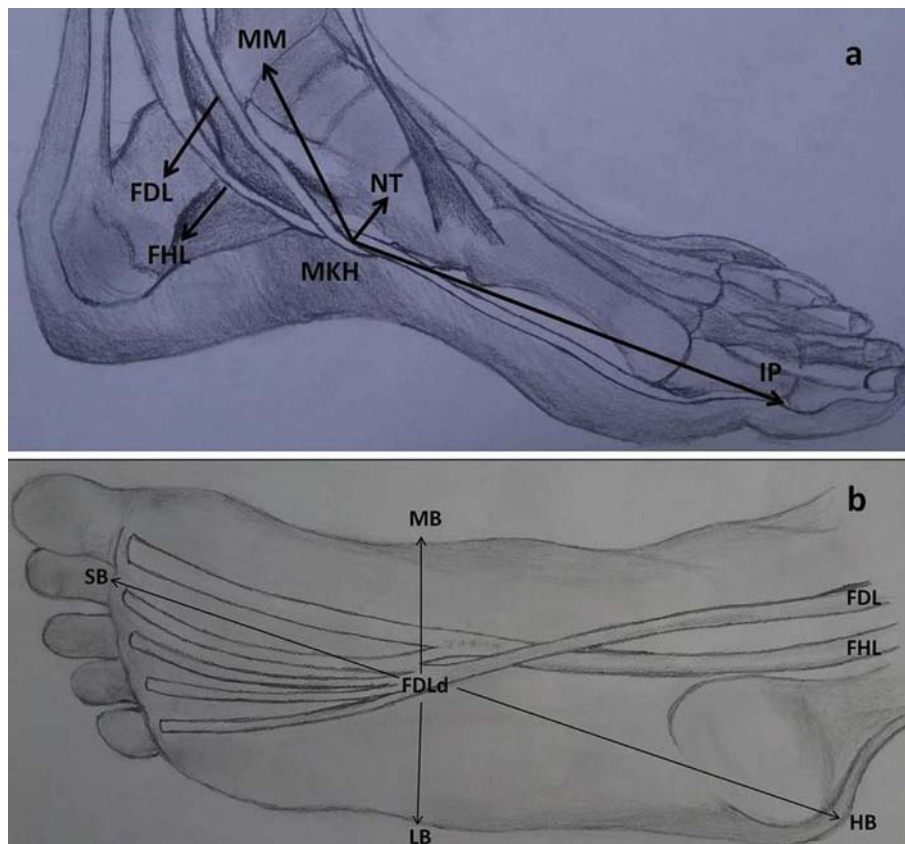


Fig. 1. The illustrations: 1a shows the distance of MKH to medial malleolus (MM), navicular tuberosity (NT) and first interphalangeal joint (IP). 1b shows the distance of FDL tendon division (FDLd) to lateral border of the foot (LB), medial border of the foot (MB), base of the second toe (SB) and back of the heel (HB).

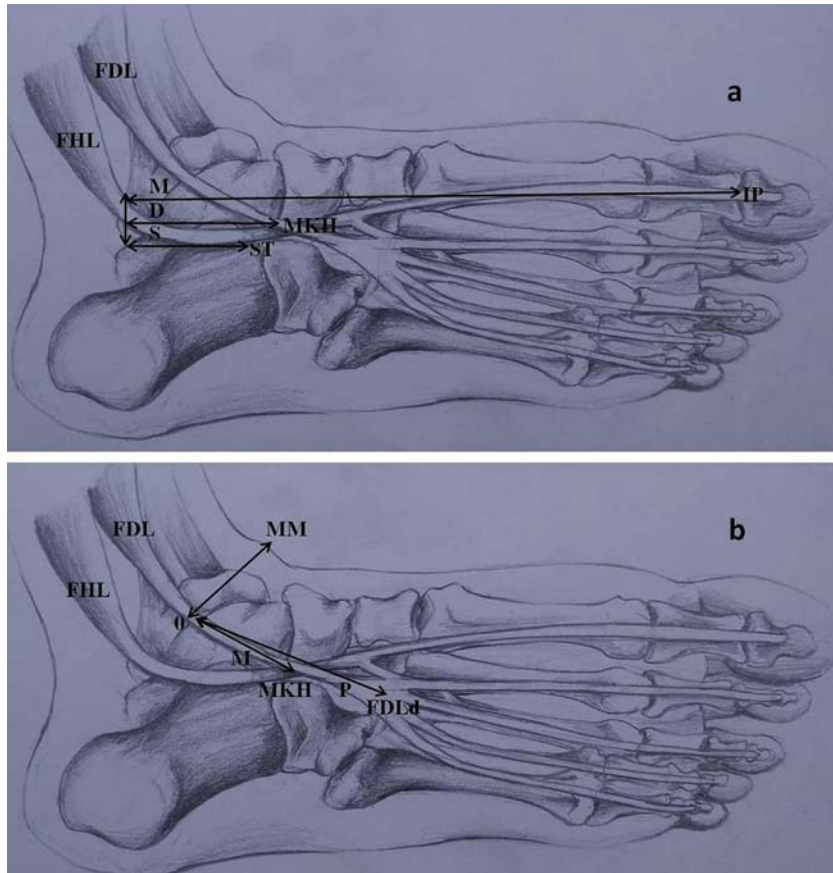


Fig. 2. The illustrations: 2a shows techniques of harvesting tendon grafts of FHL according to single (S), double (D) and minimal invasive incision (M). 2b shows techniques of harvesting tendon grafts of FDL according to medial approach (M) and plantar approach (P). Also, it shows the starting point (O) used for harvesting FDL tendon grafts and distance from this point to medial malleolus (MM). ST: Sustentaculum tali, IP: first interphalangeal joint.

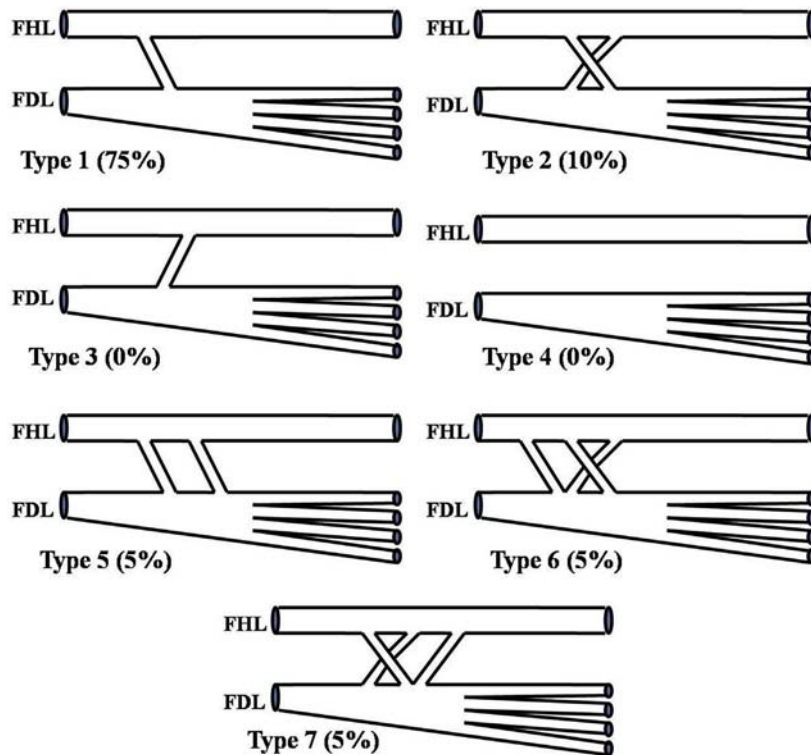


Fig. 3. The illustration shows classification of connections between tendons. Type 1, one slip from FHL to FDL; Type 2, crossed connection; Type 3, one slip from FDL to FHL; Type 4, no connection; Type 5, two slip from FHL to FDL; Type 6, two slip from FHL to FDL and one slip from FDL to FHL; Type 7, two slip from FDL to FHL and one slip from FHL to FDL.

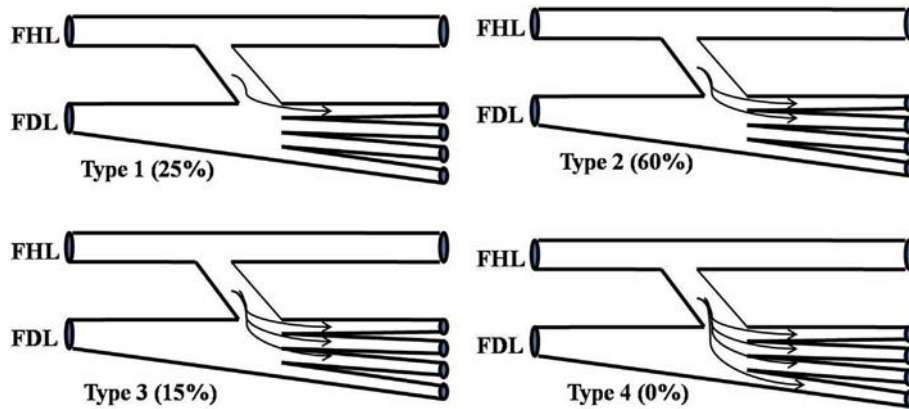


Fig. 4. The illustration shows contribution of FHL slips to long flexor tendons of toes. Type 1, contribution to toe 2; Type 2, to toes 2 and 3; Type 3, to toes 2–4; Type 4, to toes 2–5.

All the anatomical structures were photographed. Measurements were performed by the same researcher using digital caliper (0.01 mm precision). All data were statistically analyzed. A p-value of less than 0.05 was considered to be statistically significant.

Results

No significant difference was found between the sides regarding the morphometric measurements of all variables ($p > 0.05$).

The distances from proximal and distal points of slips and MKH to certain landmarks were summarized in Table 1. The measurements of the length, thickness and width of tendons and slips were given in Table 2. The differences regarding length, width and thickness of proximal and distal parts of FDL were found to be statically significant ($p < 0.001$). The difference in length and width between proximal and distal parts of FHL was found to be statistically significant ($p < 0.001$), while there was no difference in terms of thickness ($p = 0.053$).

The average lengths of FHL and FDL tendon grafts harvested by different incision techniques and the measurements between certain landmarks and variables were given in Table 3. In comparing the FHL graft lengths, the difference was found to be statistically significant ($p < 0.001$). There was also significant difference between FDL tendon graft lengths depending on the harvesting method, medial or plantar approach ($p < 0.001$). Frequencies of the connections between FHL and FDL and the participation of FHL slips to long flexor tendons of toes were given in Figs. 3 and 4. The distribution of slips was found to be type 1 in 7 cadavers, bilaterally. In one of remaining 3 cadavers, there was type 2 in left foot, while type 7 was observed in right foot (Fig. 5a). In the second, there was type 5 in left foot (Fig. 5b), while type 6 in right foot (Fig. 5c). In the third, one cross-connection was seen in right foot, however, a net-like conjoint tendon composed by FHL, FDL and medial head of FDA was observed in the left foot (Fig. 6a and b). Despite the fact that the course of slip in the conjoint tendon was as in type 1, it contained more tendinous fibers and incorporated with the fibers from the

Table 1
Distances between the certain landmarks and variables.

Variables	N	The mean of Foot Length ±SD (range) ^a	Medial malleolus ±SD (range) ^a	First interphalangeal joint ±SD (range) ^a	Navicular tuberosity ±SD (range) ^a
MKH	20	23.23 ± 1.30 (21.50–26.50)	5.93 ± 0.74 (4.72–7.35)	12.61 ± 1.11 (10.33–14.09)	1.75 ± 0.39 (1.11–2.44)
S1 proximal point	19	23.30 ± 1.29 (21.50–26.50)	5.89 ± 1.08 (35.98–80.33)	12.39 ± 1.10 (9.99–14.38)	1.84 ± 0.53 (1.05–2.88)
S1 distal point	19	23.30 ± 1.29 (21.50–26.50)	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	22.47 ± 0.68 (21.50–23.00)	5.50 ± 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	22.47 ± 0.68 (21.50–23.00)	6.56 ± 0.80 (5.56–7.52)	10.55 ± 1.42 (8.59–12.24)	1.98 ± 0.60 (1.57–2.99)

N: number of sides, S1: slip from FHL to FDL, S2: slip from FDL to FHL.
^a cm.

Table 2
Morphometric measurements of FHL, FDL and slips.

Variables	N	The mean of Foot Length ±SD (range) ^a	The mean of width ±SD (range) ^a	The mean of length ±SD (range) ^b	The mean of thickness ±SD (range) ^a
Proximal FHL	20	23.23 ± 1.30 (21.50–26.50)	5.73 ± 0.53 (4.95–6.81)	7.07 ± 0.85 (5.75–8.80)	2.75 ± 0.32 (2.15–3.42)
Distal FHL	20	23.23 ± 1.30 (21.50–26.50)	3.81 ± 0.65 (2.52–4.88)	12.43 ± 1.26 (8.80–14.10)	2.96 ± 0.46 (2.01–3.77)
Proximal FDL	20	23.23 ± 1.30 (21.50–26.50)	4.57 ± 0.66 (3.36–5.75)	7.59 ± 1.07 (5.07–9.20)	2.44 ± 0.39 (1.79–3.18)
Distal FDL	20	23.23 ± 1.30 (21.50–26.50)	5.45 ± 0.76 (4.42–6.63)	13.20 ± 0.84 (11.43–14.74)	1.74 ± 0.37 (1.06–2.41)
S1	19	23.30 ± 1.29 (21.50–26.50)	2.99 ± 1.39 (1.31–6.34)	2.93 ± 1.25 (0.76–5.37)	0.99 ± 0.34 (0.38–1.47)
S2	4	22.47 ± 0.68 (21.50–23.00)	1.97 ± 0.49 (1.21–2.49)	1.72 ± 0.91 (0.75–3.19)	0.94 ± 0.39 (0.30–1.31)
S1 + S2	19	23.30 ± 1.29 (21.50–26.50)	2.79 ± 1.32 (1.21–6.34)	2.70 ± 1.27 (0.75–5.37)	0.84 ± 0.37 (0.30–1.47)

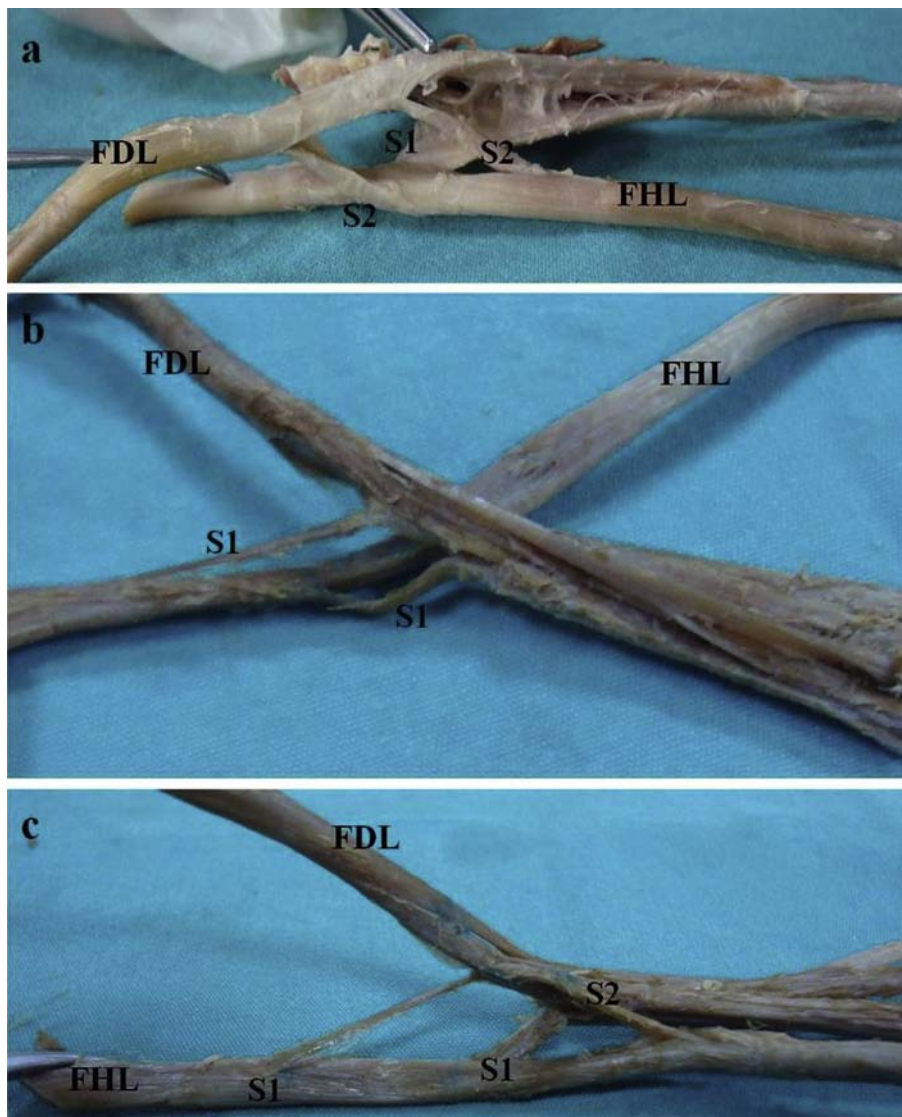
N: number of sides, S1: slips from FHL to FDL, S2: slips from FDL to FHL.
^a mm.
^b cm.

Table 3

Tendon graft lengths of FHL and FDL with different incision techniques and the distance between certain landmarks and variables.

Techniques	N	Distance from point to landmarks	mean of the length \pm SD (range) ^a
Plantar approach	20	The mean of Foot Length	23.23 \pm 1.30 (21.50–26.50)
	20	Back of heel to FDLd	11.04 \pm 0.95 (10.01–13.37)
	20	Base of second toe to FDLd	8.46 \pm 0.58 (7.08–9.37)
	20	FDLd to lateral border of foot	3.38 \pm 0.30 (2.43–3.80)
	20	FDLd to medial border of foot	3.31 \pm 0.29 (2.78–3.97)
	20	FDL tendon graft length	9.37 \pm 0.77 (8.08–10.69)
	20	FDL tendon to tip of medial malleolus	2.92 \pm 0.24 (2.42–3.39)
Medial approach	20	Length of the incision line	8.65 \pm 0.63 (7.75–9.84)
	20	FDL tendon graft length	6.14 \pm 0.60 (4.61–7.08)
Single incision technique	20	FHL musculotendinous junction to ST	5.75 \pm 0.63 (4.52–6.86)
Double incision technique	20	FHL musculotendinous junction to MKH	7.03 \pm 0.86 (5.77–8.8)
Minimal invasive technique	20	FHL musculotendinous junction to IP	20.22 \pm 1.32 (16.82–21.97)

ST: Sustentaculum tali, IP: first interphalangeal joint.

^a cm.**Fig. 5.** The photographs: 5a shows one slip from FHL to FDL (S1) and two slips from FDL to FHL (S2), 5b shows two slips from FHL to FDL (S1) and 5c shows two slips from FHL to FDL (S1) and one slip from FDL to FHL (S2).

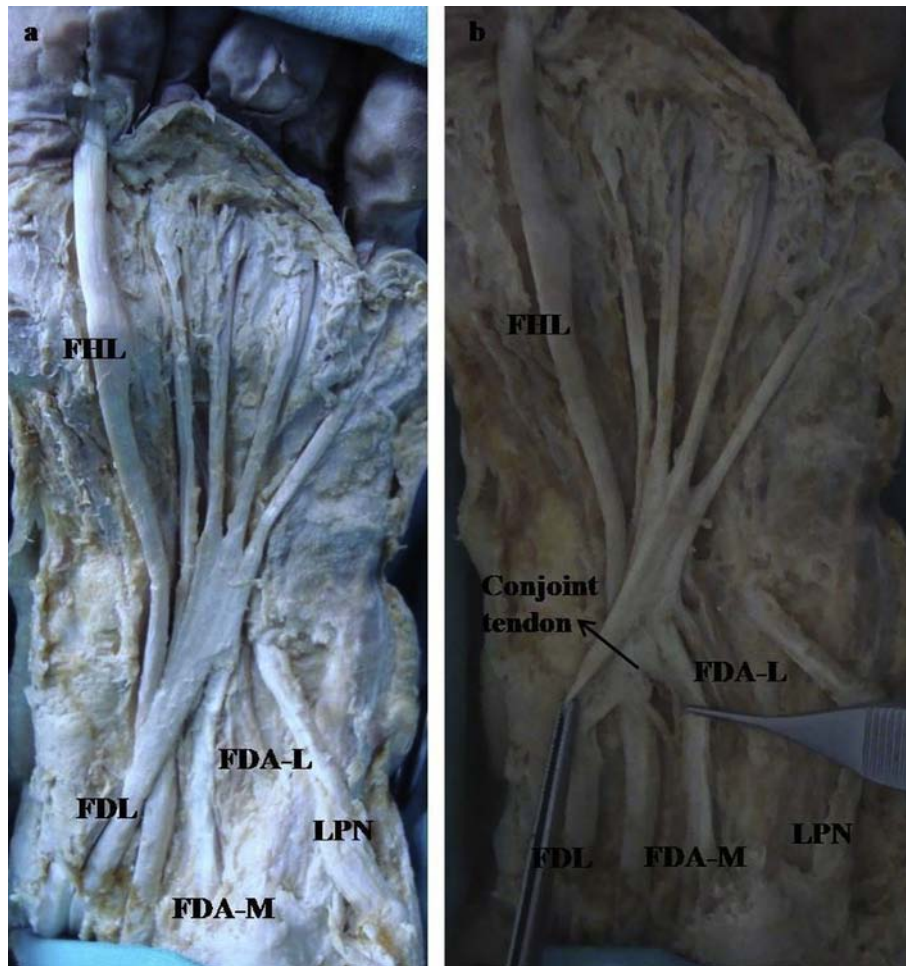


Fig. 6. The photograph 6a, b show a net-like conjoint tendon composed by FHL, FDL and medial head of FDA (FDA-M) and also show lateral head of FDA (FDA-L) and lateral plantar nerve (LPN).

medial head of FDA. All the connections between FHL and FDL tendons were found to be distal to the MKH and proximal to FDL tendon division (Fig. 7). The average distance between MKH and FDL tendon division was 2.71 ± 0.58 (range, 1.99–3.68) cm. In addition, the average foot length was found as 23.23 ± 1.30 (range, 21.50–26.50) cm.

In all sides, FDA was innervated by lateral plantar nerve (Fig. 8). In 4 out of 20 sides, medial head of FDA had prominent tendinous fibers. In 3 of those sides, half of the medial head was composed of tendinous fibers (Fig. 9a) while in one it was mostly tendinous (Fig. 6a and b). In these four feet, the tendinous fibers of FDA participated into long flexor tendons of toes 2–5. Data of the attachments sites of FDA were given in Table 4 (Figs. 7–9).

Discussion

Current study: firstly, provided some important anatomical parameters with surgical relevance such as the lengths of the tendon graft of both FHL and FDL. Second of all, considering the lack of understanding up to date, the exact location of MKH and related slips were detailed. Besides, differing with the existed classifications,^{6,8,17–21} our study revealed two new types of connection in the region.

Location of MKH

Anatomical location of MKH plays an important role in harvesting FHL tendon graft with double incision technique and FDL tendon graft with medial approach.^{2,4,5} To our knowledge, data about exact location of MKH was limited with the study of Mao et al.⁶ Contrast to them in this study, MKH was found to be more proximal to first interphalangeal joint, deeper to navicular tuberosity and in addition 5.93 ± 0.74 cm distal to medial malleolus.

Tendon grafts of FHL

Several reports have given successful outcomes with the usage of FHL tendon grafts, especially in Achilles tendon repair surgeries.^{25,26} Besides, Spratley et al.²⁷ proposed using FHL tendon grafts instead of FDL tendon grafts in posterior tibial tendon dysfunction. However, nerve injuries or toe deformities after FHL tendon transfers were also reported, particularly while harvesting this tendon distal to the MKH.²⁸ The additional length, obtained by the double incision technique as compared to the single incision technique in our study was shorter than the tendon graft lengths reported as 1.64 cm by Mao et al.⁶ and



Fig. 7. The photograph shows slip (S1, from FHL to FDL) between MKH and FDL tendon division (FDLd). Also, it shows attachments of FDA to deep surface of FDL and FHL slip (S1).

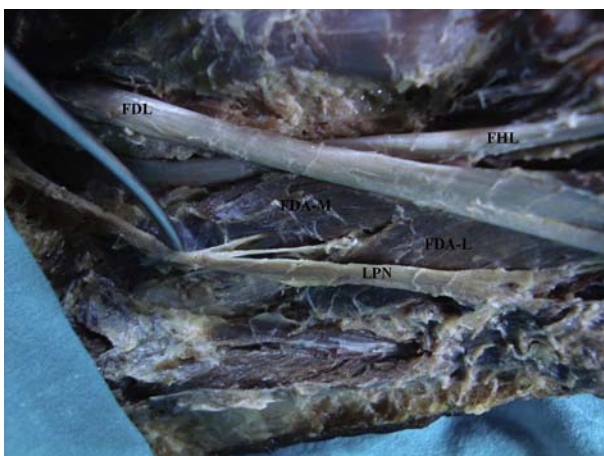


Fig. 8. The photograph shows FDA innervation and attachments of FDA to lateral margin of FDL. Also, it shows medial head of FDA (FDA-M), lateral head of FDA (FDA-L) and lateral plantar nerve (LPN).

2.93 cm by Tashjian et al.⁵ On the other hand, tendon graft length harvested by minimal invasive incision technique was limited in study of Mao et al.⁶ In our study, additional tendon graft length harvested by the same technique was 2.73 cm longer than results of Mao et al.⁶

Tendon grafts of FDL

Tendon grafts of FDL have been used in posterior tibial tendon dysfunction.^{11,29} Tendon grafts, obtained by diverse surgical

approaches, were fixed to navicular within drill holes with different fixators.^{30–32} In the study of Park et al.,⁴ the incision line started 3 cm above the tip of medial malleolus then curved about 9 cm to navicular tuberosity. The obtained tendon graft length was 6.7 cm,⁴ which was similar to the findings of our study. They also expressed that length was enough for treatment of posterior tibial tendon dysfunction.⁴ On the other hand, Sullivan et al.³³ stated the need of longer tendon grafts in some surgical procedures as a result of their investigation where different fixation techniques were compared. In considering the medial approach, tendon grafts may either be sutured back onto itself after passing through the navicular drill holes, or may be secured to the bone with non-absorbable sutures and bone anchors.^{15,16,30–32} When harvesting longer tendon grafts, the use of direct plantar approach, also known as minimal invasive technique is essential.^{15,16} Our mean graft length harvested by this technique was concordant with the findings of Panchbhavi et al.¹⁶ (9 cm). However, our findings of FDL tendon separation level was differing from theirs as found to be more distal and lateral levels.

The connections between FHL and FDL tendons

Connections between FHL and FDL are critically of importance for harvesting tendon grafts.⁸ The most important advantage of these connections is that they act as a natural tenodesis during harvesting tendon grafts from proximal to MKH.¹⁸ In contrast, the most critical disadvantage is the requirement of additional procedures due to the interruption of connections during the minimal invasive incision technique for harvesting FHL and FDL tendon grafts.⁶ Therefore, the anatomical awareness of the connections between tendons and also their variations is crucial for the surgeons. Our findings about the connections between these tendons and the participation of FHL slips to toes differ from the past studies (Tables 5 and 6).^{6,8,17–21,23,34} The difference between those results can be explained by number of samples and racial and ethnic factors.^{6,8} On the other hand, two new types of connections (Type 6 and 7) were defined in the current study.

Anatomical connections, especially when harvesting tendon grafts from distal to MKH by minimal invasive technique has been considered significant.⁸ Mao et al.⁶ stated that with the mentioned technique, in obtaining FHL tendon graft, connections from FHL to FDL must be cut with a separate incision by employing the medial or direct plantar approach. Accordingly they suggested an incision line that starts from MKH and extends distally,⁶ however yet the exact length of mentioned incision remains to be elusive. Panchbhavi et al.¹⁵ reported that, an incision of 1.98 ± 0.15 cm long that proximally extends from FDL tendon division would be adequate for harvesting maximum tendon graft and cutting slips from FDL to FHL. In the study of Oddy et al.¹⁴ which compared the harvesting techniques of FDL tendon grafts, they stated that the plantar approach was more beneficial as compared with the medial approach. They also found that an additional 2.29 ± 0.36 cm long tendon graft which could be isolated by a 1.56 ± 0.47 cm longer incision and further by cutting the connections of FDL to FHL.¹⁴ Despite applying the same techniques, the incidence of connections between FHL and FDL tendons was significantly varied between these two studies.^{14,15} In the study of Panchbhavi et al.,¹⁵ connections were found in 11 of 83 feet (13.25%) while in the study of Oddy et al.¹⁴ it was present in all feet except one. There was an incompatibility between the study of Panchbhavi et al [23] and several other studies.^{6,8,18,21} Similar to our findings, Oddy et al.¹⁴ mentioned that connections between FHL and FDL tendons were proximal to FDL tendon division. Connections between these tendons were

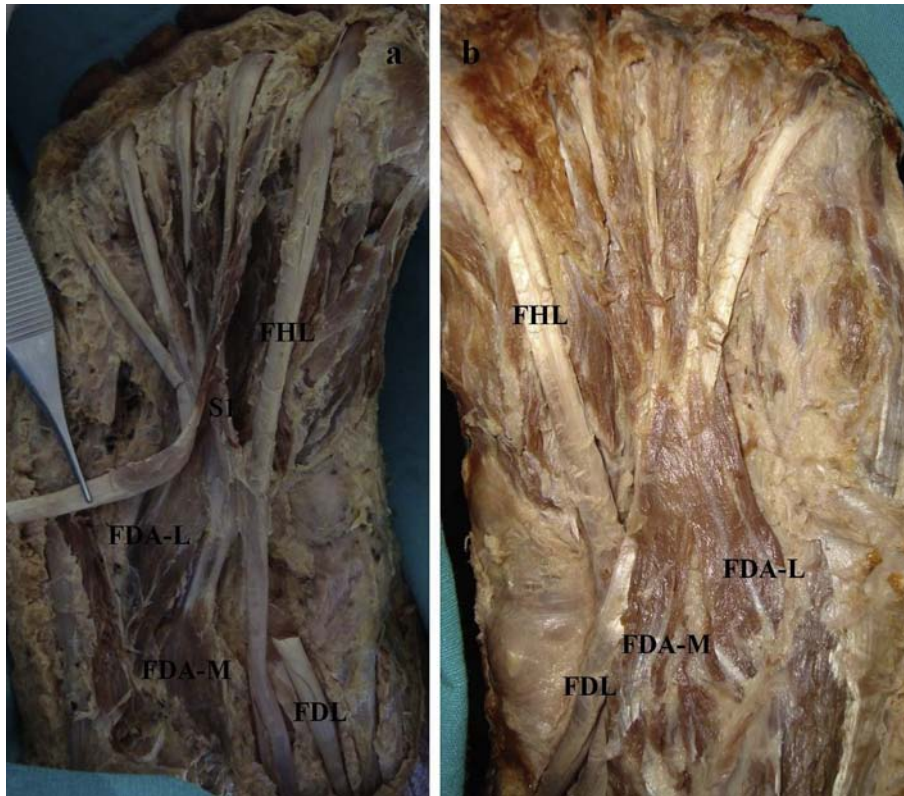


Fig. 9. The photograph 9a shows half of the medial head composed of tendinous fibers and attachments of FDA to FHL slip and also 9b shows attachment of FDA to superficial surface of FDL. They show medial head of FDA (FDA-M) and lateral head of FDA (FDA-L).

Table 4
Attachments of FDA at MKH.

Attachment	N	%
FHL slip	6	30
FHL slip + DS	4	20
FHL slip + DS + LM	1	5
FHL slip + LM + SS	5	25
FHL slip + DS + LM + SS	4	20

N: number of sides, LM: lateral margin of FDL, DS: deep surface of FDL, SS: superficial surface of FDL and FHL slip: slip from FHL to FDL.

placed distal to MKH and proximal to FDL tendon division in our study, therefore those reference points were accepted as the borders of incision line. In short, it would be possible to cut slips coursing FHL to FDL, an average of 2.71 cm distally to the MKH. At the same time, it would also be possible to cut slips coursing FDL to FHL, 2.71 cm proximal to FDL tendon division and harvest longer FDL tendon grafts. In any case, the area of the tendon graft should not be ignored when taken by minimal invasive technique

Table 6
Connection of FHL slips to toes in previous studies.

Study	toe 2 (%)	toes 2–3 (%)	toes 2–4 (%)	toes 2–5 (%)
This study	25	60	15	0
Edama et al. ¹⁷	37	54	9	0
Hur et al. ²³	8	64	28	0
Mao et al. ⁶	31	61	8	0
Plaass et al. ⁸	33	55	7	0
Testut et al. ³⁴	22	40	36	2

distal to MKH. Mulier et al.²⁰ suggested that harvesting tendon graft distal to MKH could lead to serious nerve injuries when harvesting FHL tendon grafts with double incision technique. On the other hand, some other reports pointed out that the tendon grafts could be isolated safely based on the priority measuring the distance from FDL tendon division to lateral and medial plantar nerves.^{14–16} Also, it is important to be aware of number of connections between tendons, while harvesting tendon grafts distal to MKH.

Table 5
Distribution of connections between FHL and FDL in previous studies.

Study	N	Type 1 (%)	Type 2 (%)	Type 3 (%)	Type 4 (%)	Type 5 (%)	Type 6 (%)	Type 7 (%)
This study	20	75	10	0	0	5	5	5
Edama et al. ¹⁷	100	86	3	0	0	11	0	0
LaRue et al. ¹⁸	24	42	41	0	17	0	0	0
Mao et al. ⁶	64	96	4	0	0	0	0	0
Martin ¹⁹	33	88	6	0	6	0	0	0
Mulier et al. ²⁰	24	58	29	0	13	0	0	0
O'Sullivan et al. ²¹	16	68	19	13	0	0	0	0
Plaass et al. ⁸	60	67	30	3	0	0	0	0

N: number of sides.

Attachment sites of FDA

There are several reported variations at the attachment sites of FDA.^{22,23} For instance, Athavale et al²² reported frequent FDA insertion to various surfaces of FDL and in far fewer to FHL slips. According to the results of Hur et al,²³ insertion site of FDA was mainly consisted of FHL slips. Similarly, FDA was observed to be inserting to FHL slips in all the feet in our study. In four of the all feet, the medial head was observed to be composed of markedly fibrous fibers. In one of those four, even unusual to literature, the medial head was found to be completely tendinous. On that side, medial tendinous head of FDA was observed as forming a common tendon, in conjunction with FDL and FHL tendons. Hur et al²³ reported that FDA participated in the structure and function of long flexor tendons of small toes via the connections to FHL slips. Therefore, it was suggested that formation of long flexor tendons of lesser toes are formed by FDL, FDA and FHL slips.

Conclusions

In the light of our current findings, it is suggested that FHL, FDL and FDA formed the function and formation of long flexor tendons of lesser toes. Therefore, harvesting FHL and FDL tendon grafts with minimal invasive technique from distal to MKH may lead to a functional loss in lesser toes motion by damaging the FHL slips which are the main attachment site of FDA. Finally, the freshly described two types (Type 6 and 7) will serve as an important consideration to the surgeons.

Conflicts of interest

The authors declare that they have no conflict of interest.

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