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ORIGINAL ARTICLE

Communications between the tendons of flexor hallucis longus and flexor digitorum longus: a cadaveric study

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Abstract

Introduction Tibialis posterior tendon insufficiency in adult acquired flat foot deformity (AAFFD) is treated by reinforcing the posterior tibial tendon (PTT) using grafts from flexor hallucis longus (FHL) and flexor digitorum longus (FDL). The communication between FHL and FDL will influence the length of the graft that can be harvested from FHL and FDL. In this study, we aim to study the patterns of communications between FHL and FDL tendons and the location of Master Knot of Henry (MKH) and point of division of FDL tendons in Indian population.

Materials and methods In this observational descriptive study, 36 formalin-fixed cadavers were sourced from Subbaiah Institute of Medical Sciences, Shimoga, Karnataka, India, and JIPMER, Puducherry, India, during the period of 2017–19. Various parameters of the foot to locate the MKH and point of division of FDL tendons and various types of communications between FHL and FDL were observed.

Results Among the various types of communications between FHL and FDL tendons, type I was present in 61.76% of cases, type II in 2.94% of cases, type III in 7.35% of cases, type IV in 14.70% of cases, type V in 8.82% of cases, type VI in 0% of cases, type VII in 1.47% of cases and an unusual type in 2.94% of cases.

Conclusion In the present study done in Indian population, we found that type I variety is present more commonly followed by type IV. FHL and FDL tendon grafts can be lengthened based on the communications between them. In type I variety, the communication can be severed at the FDL end to lengthen the tendon graft for harvest.

Keywords Communications · Flexor digitorum longus · Flexor hallucis longus · Master Knot of Henry · Tibialis posterior

Introduction

Tendon grafts for reconstructive surgeries involving foot are usually harvested from flexor hallucis longus and flexor digitorum longus [3, 19, 21]. Turner in 1866 observed that in the long flexors of the thumb and fingers, in addition to the variations in bulk, extent of attachment and mode of division, there were modified arrangements of bands connecting them together. They are found to be either attaching to the muscles or division of muscles [28]. In the mid-foot region, these two tendons cross each other deep to the abductor hallucis muscle. The zone of crossing, famously named as the Master Knot of Henry (MKH), has the two tendons being covered by fibrous tissue and communicating with each other by means of fibrous slips. The knot is used as a landmark during reconstruction procedures because even if one of these tendons is transferred beyond the level of the master knot, functions of the digits would still be continuing without impairment [24]. The knowledge regarding it is also helpful in determining the direction of spread of deep space infection in case of diabetic foot [10]. Especially, the tendinous sheath overlying FHL acts as a source of potential transmission of infection across compartments [1]. Johnson et al. suggested that performing the sub-talar arthrodesis combined with flexor digitorum transfer is an effective and reliable procedure for correcting hindfoot valgus deformity as well as forefoot abduction by restoring the height of the longitudinal arch [8]. The anatomical variations in the communications between the FHL and FDL tendons (MKH) and the variations in the location of division of FDL tendon will impact the planning of the size and length of tendon transfer

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graft [12]. Errors during the tendon-harvesting surgery may result in multiple postoperative complications such as the weakness in the little toes, wound morbidity and neurovascular injury [25, 27]. In this study, we aim to study the patterns of communications present between the FHL and FDL tendons, and the location of MKH and point of division of FDL tendons in the Indian population.

Materials and methods

In this observational descriptive study, 36 formalin-fixed cadavers ($R = 32$, $L = 36$) sourced from Subbaiah Institute of Medical Sciences, Shimoga, Karnataka, and JIPMER, Puducherry, during the period 2017–19 were included. The limbs with foot deformity or any pathological condition were excluded from the study. The cadavers were positioned in supine position and the skin of the sole was reflected by making a "U"-shaped incision extending from the right border of the foot to the left. The superficial fascia and the plantar aponeurosis were reflected to expose the muscular layers of sole. The first layer of muscles such as abductor hallucis, abductor digiti minimi and flexor digitorum brevis were severed proximally at their origin and reflected distally to expose the second layer of muscles of the sole. The FHL and FDL muscles were separated from the adjacent connective tissue and from the underlying 3rd layer of muscles of the sole such as flexor hallucis brevis (FHB) and adductor hallucis. Both FHL and FDL tendons were traced distally till their insertion and the communications between them were observed. The location of MKH and the location of point of division of FDL were observed using the following parameters:

1. Distance between the point of MKH and the 1st interphalangeal joint.
2. Distance between the point of MKH and navicular tuberosity.
3. Distance between the point of MKH and medial malleolus.
4. Distance between the point of division of FDL tendon and the base of the 2nd toe.
5. Distance between the point of division of FDL tendon and back of heel.
6. Distance between the point of division of FDL tendon and medial border of foot.
7. Distance between the point of division of FDL tendon and lateral border of foot.

Figure 1 shows the schematic diagram of measurement of parameters taken to locate the MKH. Figure 2 shows the schematic diagram of the measurement of parameters taken to locate the point of division of FDL tendon. The

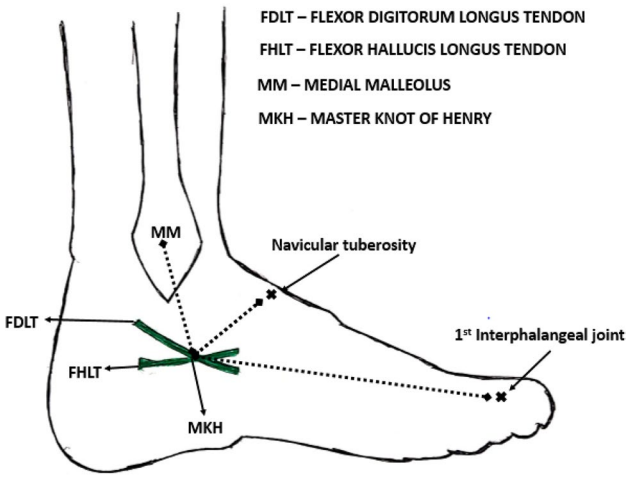

Fig. 1 Schematic diagram of foot showing the measurements of parameters taken to locate the Master Knot of Henry. *FDLT* flexor digitorum longus tendon, *FHLT* flexor hallucis longus tendon, *MM* medial malleolus, and *MKH* Master Knot of Henry

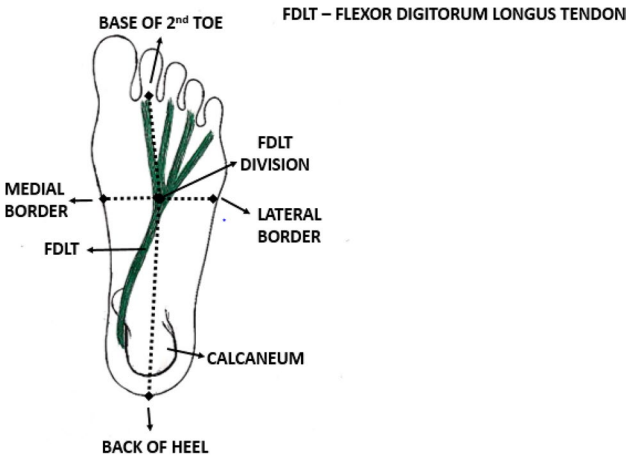

Fig. 2 Schematic diagram of the foot showing the measurement of parameters taken to locate the point of division of flexor digitorum longus tendon. *FDLT* flexor digitorum longus tendon, *FDLT division* flexor digitorum longus tendon division

communications present between the tendons of FHL and FDL are classified based on the classification proposed by Beger et al. [2]. Figure 3 shows the schematic diagram of the classification of the communications between the tendons of FHL and FDL.

All the parameters were presented as range, mean and standard deviation. Student's '*t*' test was done to measure the significance of difference between the right and left sides and a p value of less than 0.005 was considered to be statistically significant.

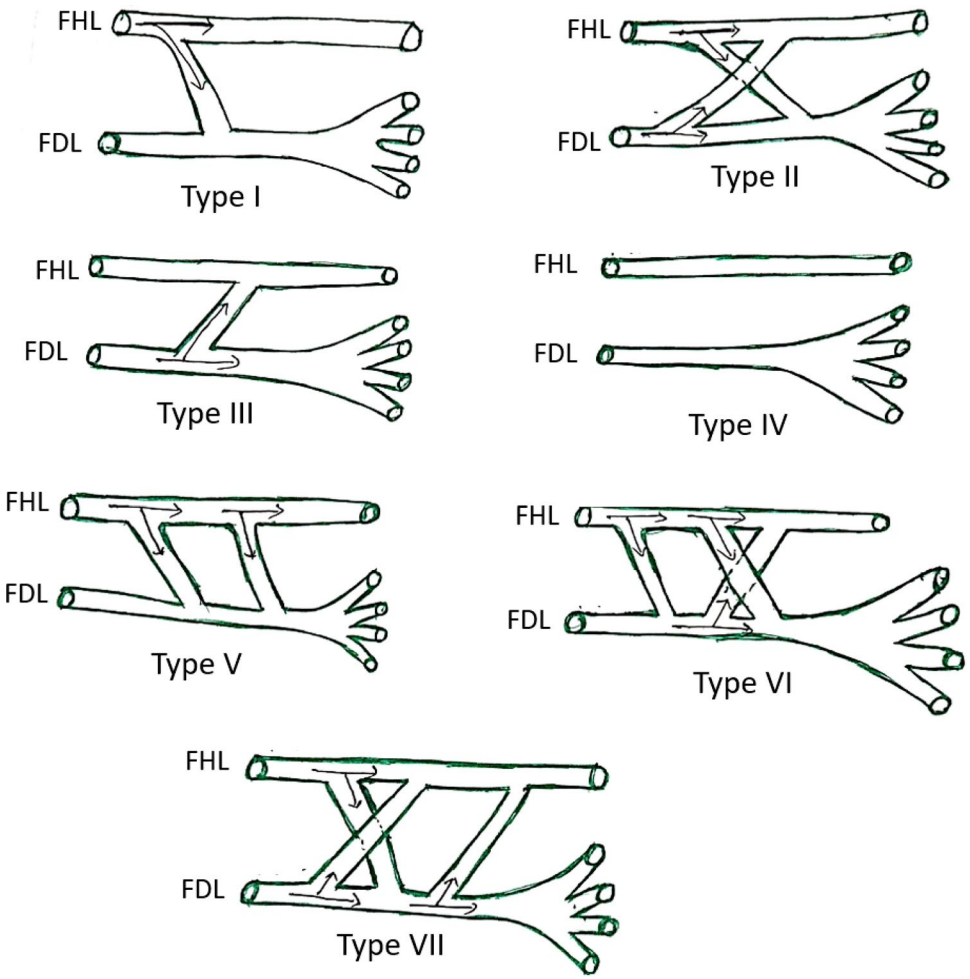

Fig. 3 Schematic diagram showing the classification of the communications between the tendons of FHL and FDL proposed by Beger et al. [3]. *FHL* flexor hallucis longus and *FDL* flexor digitorum longus

Results

The location of Master Knot of Henry

The distance between the point of crossing of FHL and FDL tendons (MKH) and the 1st interphalangeal joint:

The mean distance between the point of crossing of FHL and FDL tendons (MKH) and the 1st interphalangeal joint on the right and left sides was 125.02 ± 8.93 mm and 119.68 ± 11.14 mm, respectively. The mean distance on the right side was found to be greater than the left side. The difference of measurements between the right side and left side was statistically significant.

The distance between the point of crossing of FHL and FDL tendons (MKH) and the navicular tuberosity:

The mean distance between the point of crossing of FHL and FDL tendons (MKH) and the navicular tuberosity on the right and left sides was 32.36 ± 9.32 mm and 29.98 ± 9.58 mm, respectively. The mean distance on the right side was found to be greater than the left side. However, the difference of measurements between the right side and left side was statistically insignificant.

The distance between the point of crossing of FHL and FDL tendons (MKH) and the medial malleolus:

The mean distance between the point of crossing of FHL and FDL tendons (MKH) and the medial malleolus on the right and left sides was 61.04 ± 11.69 mm and 60.77 ± 12.49 mm, respectively. The mean distance on the right side was found to be greater than the left side. However, the difference of measurements between the right side and left side was statistically insignificant.

The location of division of flexor digitorum longus tendon

The distance between the point of division of FDL and the 2nd toe:

The mean distance between the point of division of FDL tendon and the 2nd toe on the right and left sides was 96.69 ± 12.06 mm and 94.72 ± 13.68 mm, respectively. The mean distance on the right side was found to be greater than the left side. However, the difference of measurements between the right side and left side was statistically insignificant.

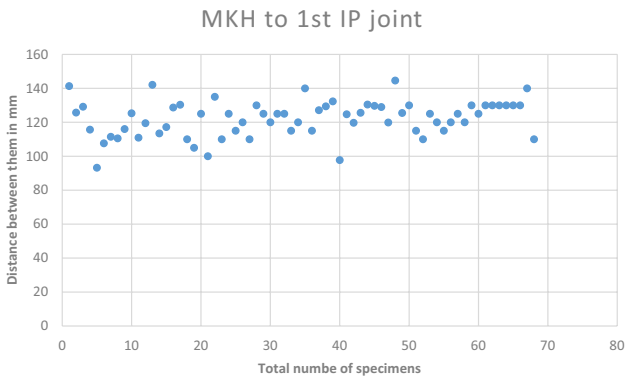

Fig. 4 Scattered diagram showing the distribution of distance between MKH and the 1st interphalangeal joint (mm). *MKH* Master Knot of Henry and *IP joint* interphalangeal joint

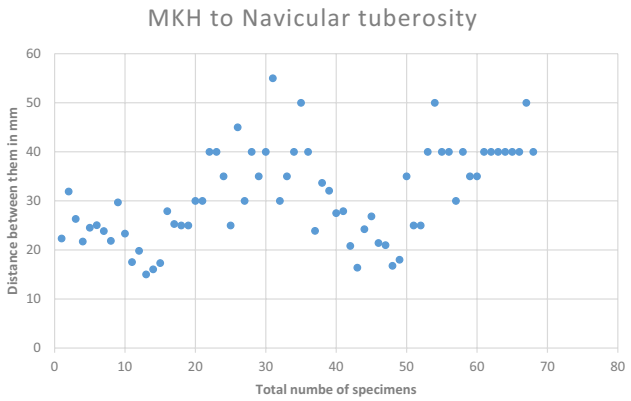

Fig. 5 Scattered diagram showing the distribution of distance between MKH and navicular tuberosity (mm). *MKH* Master Knot of Henry

The distance between the point of division of FDL tendons and the back of heel:

The mean distance between the point of division of FDL tendon and the back of the heel on the right and left sides was 95.13 ± 17.13 mm and 92.52 ± 17.66 mm, respectively. The mean distance on the right side was found to be greater than the left side. However, the difference of measurements between the right side and left side was statistically insignificant.

The distance between the point of division of FDL tendons and the medial border of foot:

The mean distance between the point of division of FDL tendon and the medial border of the foot on the right and left sides was 31.07 ± 9.46 mm and 27.56 ± 7.72 mm, respectively. The mean distance on the right side was found to be greater than the left side. The difference of measurements between the right side and left side was statistically significant.

The distance between the point of division of FDL tendons and the lateral border of foot:

The mean distance between the point of division of FDL tendons and the lateral border of the foot on the right and left sides was 41.42 ± 4.8 mm and 40.62 ± 5.53 mm, respectively. The mean distance on the right side was found to be greater than the left side. However, the difference of measurements between the right side and left side was statistically insignificant.

The distribution of various parameters with respect to the location of MKH and point of division of FDL is depicted in Figs. 4, 5, 6, 7, 8, 9, and 10. The morphometric parameters and the different types of communications between FHL and FDL tendons in both the limbs observed in the present study are summarized in Tables 1 and 2, respectively. The total percentage distribution of types of communications is plotted in Fig. 11.

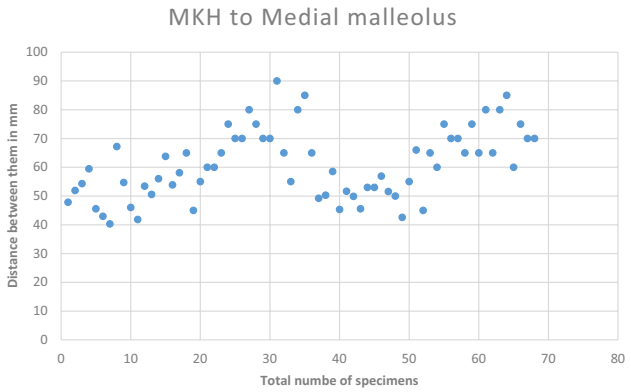

Fig. 6 Scattered diagram showing the distribution of distance between MKH and medial malleolus (mm). *MKH* Master Knot of Henry

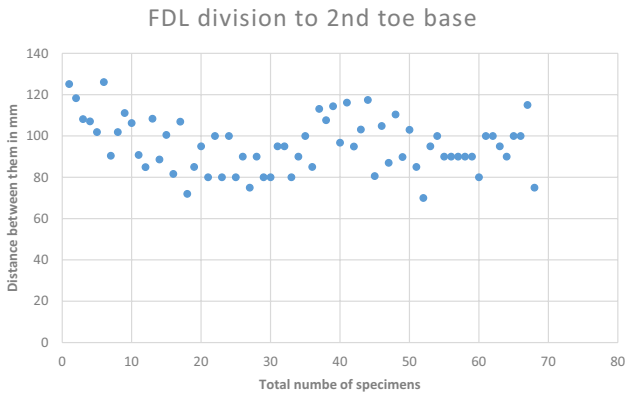

Fig. 7 Scattered diagram showing the distribution of distance between the point of division of FDL and the 2nd toe (mm). *FDL* flexor digitorum accessorius

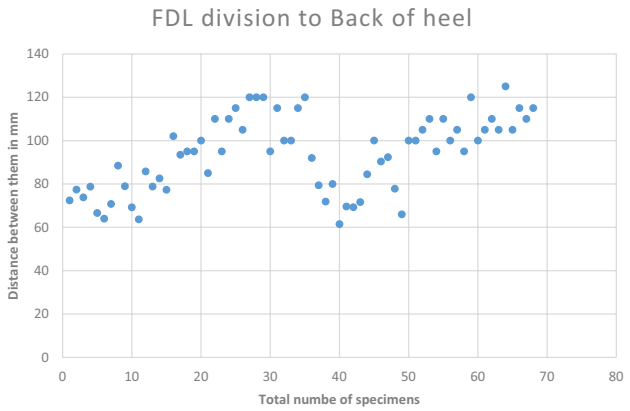

Fig. 8 Scattered diagram showing the distribution of distance between the point of division of FDL and the back of the heel (mm). *FDL* flexor digitorum accessorius

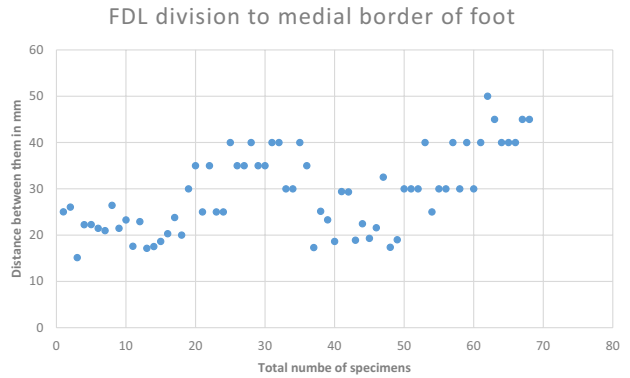

Fig. 9 Scattered diagram showing the distribution of distance between the point of division of FDL and medial border of foot (mm). *FDL* flexor digitorum accessorius

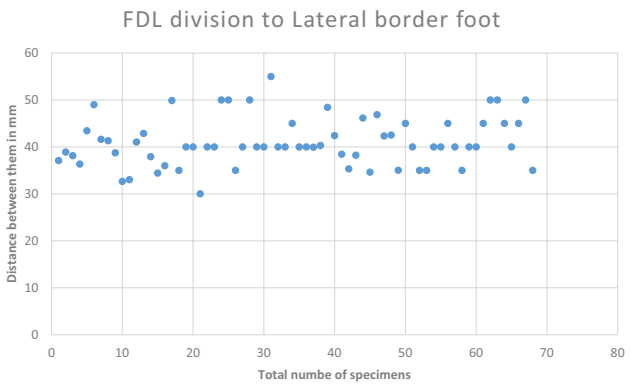

Fig. 10 Scattered diagram showing the distribution of distance between the point of division of FDL and lateral border of foot (mm). *FDL* flexor digitorum accessorius

Discussion

MKH is the point in the plantar aspect of the foot where the long flexor tendons such as FHL and FDL cross each other with different types of communicating slips between them. Being one of the most commonly used surgical landmark in foot and ankle repair surgeries, it is important to know the location of MKH [18, 23, 27]. It has been suggested that the incision line made distally from MKH point would be better for obtaining the graft [14, 22, 23]. With the adequate knowledge about the location of MKH, a smaller skin incision can be opted during surgery which can preserve the medial plantar nerve and vessels, thereby reducing the wound morbidity [25, 27].

The FDL muscle is one of the long flexor muscles in the leg and foot. It originates from the posterior surface of the tibia, just below the soleal line, medial to the tibialis posterior muscle and also from the fascia covering the tibialis posterior muscle. The muscle ends in a tendon which curves behind the medial malleolus along with tibialis posterior muscle in a separate fascial compartment. FDL crosses superficial to the FHL tendon in plantar aspect of foot (MKH) and it receives few tendinous connecting slips from FHL. The FDL in turn contributes few slips to the FHL and finally divides into four slips for the lateral four toes (near the middle of the foot). Surgical incisions made proximal to the point of division of FDL tendon will aid in obtaining the tendon graft from FDL, by avoiding any injury to the neurovascular structures present in the foot [17, 22]. Martin observed that flexor hallucis longus tendon does not always lie in the groove between the two bellies of flexor hallucis brevis. Rather, it would cross the lateral belly of FHB obliquely where it gets clamped by the distal band of the medial inter-muscular septum [16]. The distance of neurovascular bundle from FHL is variable and in the pattern where the neurovascular bundle overlaps the FHL, it needs to be separated carefully to avoid inadvertent injuries [15].

The FHL and FDL receive extraneous attachments from the surrounding foot muscles. According to Schulze, the quadratus plantae (QP) muscle does not have a boney insertion and it is distally attached to the tendon of FHL or as a tendinous slip from FHL to FDL. The QP is variably involved in the attachment to FDL tendons [1]. Lewis reported similar findings, where the QP muscle is variably involved in the composition of the chiasma plantare and gained attachments to the tendons of FHL and FDL muscles [11].

The dissection of various communications between the FHL and FDL tendons is required to procure the tendon graft of better length [17, 22]. In the present study, we observed the location of MKH and the division of FDL

Table 1 The morphometric parameters observed in this study

S. no.	Parameters (distance between)	Side	No.	Range (mm)	Mean distance (mm)	Standard deviation (mm)	*P* value
1	MKH and 1st interphalangeal joint	Right	32	97.74–144.59	125.02	8.93	0.026
		Left	36	93.24–142.10	119.68	11.14	
2	MKH and navicular tuberosity	Right	32	16.40–50	32.36	9.32	0.1
		Left	36	15.01–55	29.98	9.58	
3	MKH and medial malleolus	Right	32	42.60–85	61.04	11.69	0.381
		Left	36	40.32–90	60.77	12.49	
4	FDLT division and 2nd toe	Right	32	70–117.45	96.69	12.06	0.682
		Left	36	72–126.10	94.72	13.68	
5	FDLT division and back of heel	Right	32	61.49–125	95.13	17.13	0.078
		Left	36	63.67–120	92.52	17.66	
6	FDLT division and medial border of foot	Right	32	17.31–50	31.07	9.46	0.002
		Left	36	15.14–40	27.56	7.72	
7	FDLT division and lateral border of foot	Right	32	34.63–50	41.42	4.8	0.514
		Left	36	30–55	40.62	5.53	

MKH Master Knot of Henry and *FDLT* flexor digitorum longus tendon

Table 2 Types of communication between FDL and FHL tendons on the right and left limbs

Types of communication	Right *n* (%)	Left *n* (%)	Total *n* (%)
Type 1	22 (32.35)	20 (29.41)	42 (61.76)
Type 2	1 (1.47)	1 (1.47)	2 (2.94)
Type 3	3 (4.41)	2 (2.94)	5 (7.35)
Type 4	4 (5.88)	6 (8.82)	10 (14.70)
Type 5	1 (1.47)	5 (7.35)	6 (8.82)
Type 6	0 (0)	0 (0)	0 (0)
Type 7	0 (0)	1 (1.47)	1 (1.47)
Unusual fibers from flexor digitorum accessorius	1 (1.47)	1 (1.47)	2 (2.94)

FDL flexor digitorum accessorius and *FHL* flexor hallucis longus

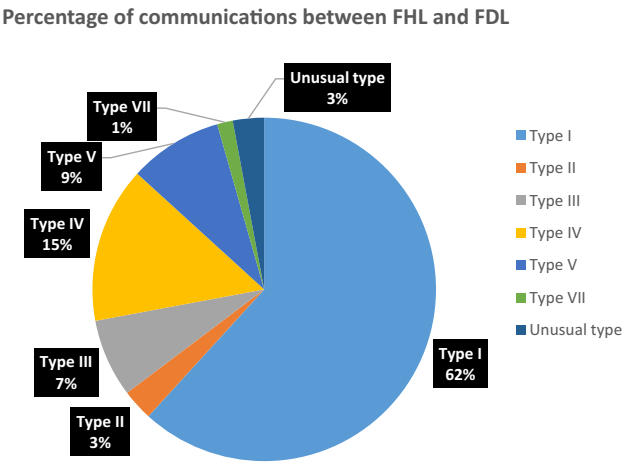

Fig. 11 Pie chart showing the percentage distribution of different types of communication between FHL and FDL tendons. *FHL* flexor hallucis longus and *FDL* flexor digitorum accessorius

tendon and measured these two anatomical events from various nearest anatomical landmarks of the foot, so as to locate them precisely. The observations from the present study are compared with the observations reported by Beger et al. in Table 3. In the present study, we observed a statistically significant difference between the right and left sides in two parameters: (a) the distance between the point of crossing of tendons of FHL and FDL (MKH) and the 1st interphalangeal joint, (b) the distance between the point of division of FDL tendons to the medial border of foot. The measurements on the right side were higher than the left side. However, there was no statistically significant difference observed in other parameters between the right and left sides. Among all the parameters, we found that the mean length between the MKH to the medial malleolus of the foot observed in the present study was similar to the study done by Beger et al. [2].

Communications between the FDL and FHL tendons:

In all types of communications, the length of the graft can be increased by including the connecting slips into the graft. The only exception is type IV. The length of the tendon graft obtained from the FDL tendon will vary based on the location of the point of division of FDL into four slips for four toes [5]. A longer length tendon graft can be obtained, if the location of point of division of FDL tendon is present more distally in the foot. Mao et al. postulated that the width of the FDL differs between the proximal and distal halves of the muscle with proximal half being wider. The QP muscle,

Table 3 Comparison of parameters measured between the present study and Beger et al. [3]

Parameters	Berger et al. (mm)	Present study (mm)
Mean foot length	232.30 ± 13	189.54 ± 30.27
Mean foot breadth	50.10 ± 7.1	70.34 ± 13.76
Mean distance between MKH and the 1st interphalangeal joint	126.10 ± 11.1	122.35 ± 10.04
Mean distance between MKH and medial malleolus	59.30 ± 7.4	60.91 ± 12.09
Mean distance between MKH and navicular tuberosity	17.50 ± 3.5	31.17 ± 9.45

MKH Master Knot of Henry

getting attached to the distal half of FDL tendon, also tends to maintain the push-off function of it [4, 26]. In addition, the tendinous slips of communication from FHL offer a stable base for toe-off movements [7]. Thus, types of communications play a crucial role in determining the degree of functional gain of toe mobility in the postoperative period.

LaRue et al. classified the configurations between FHL and FDL into following categories: in type 1, FHL tendon has attachment branching proximal to the FDL tendon. In type 2, the attachment was branching proximally from FHL tendon to FDL tendon and vice versa and type 3 had no attachment [9]. In the present study, we observed all types of communications except for type VI variety. The comparison of the different types of communications between FHL and FDL observed in the present study and the observations from the earlier studies is presented in Table 4.

Type I communication

In type I communication, there is a single slip extending from FHL tendon proximally to FDL tendon distally. In this variety, a lengthy graft can be sourced from FHL tendon by including the communicating slips present between the FHL and FDL tendons after severing the communication at FDL end. The distal stump of FHL is sutured to the 2nd toe division of FDL tendon without any functional loss [13]. Mao et al. have reported that type I communication was present in 96.9% of the observed cases. LaRue et al. have reported that type I communication was present in 42% of the observed cases. In the present study, we observed that type I communication between FHL and FDL tendons was present in 42 specimens out of 68 specimens (61.76%), and Mulier et al. (2007) reported that type I communication between FHL and FDL tendons was observed in 58% of all specimens, which is similar to our study. Among all types of communication, type I is seen to be observed in the majority of the cases in the present study and the studies done by LaRue et al., Mao et al. and Mulier et al. [9, 14, 17].

Type II communication

In type II communication, there will be two connecting slips between the FHL and FDL tendons. One of the two slips connects the FHL tendon proximally to the FDL tendon distally, and another slip connects the FDL tendon proximally to FHL tendon distally. Mao et al. have reported that type II communication was present in 0% of the observed cases. LaRue et al. have reported that type II communication was present in 42% of the observed cases. In the present study, we observed that type II communication between FHL and FDL tendon was present in 2 specimens out of 68 specimens (2.94%) and Mao et al. (2014) reported that

Table 4 Comparison of types of communications between FHL and FDL tendons observed in the present study and the previous studies

Authors	No.	Type I %	Type II %	Type III %	Type IV %	Type V %	Type VI %	Type VII %	Unusual fibers from FDA %
Martin et al. [16]	33	88	06	0	06	0	0	0	0
O'Sullivan et al. [20]	16	68	19	13	0	0	0	0	0
LaRue et al. [9]	24	42	41	0	17	0	0	0	0
Mulier et al. [17]	24	58	29	0	13	0	0	0	0
Plaass et al. [25]	60	67	30	03	0	0	0	0	0
Mao et al. [15]	64	96	04	0	0	0	0	0	0
Edama et al. [4]	100	86	03	0	0	11	0	0	0
Berger et al. [2]	20	75	10	0	0	0	05	05	0
Present study	68	61.76	2.94	7.35	14.70	8.82	0	1.47	2.94

FHL flexor hallucis longus, *FDL* flexor digitorum longus and *FDA* flexor digitorum accessorius

type II communication between FHL and FDL tendons was observed in 4% of all specimens which is similar to our study. The results of LaRue et al. are in contrast to the observations made in the present study and the study by Mao et al. [9, 14, 15]. A larger length FHL tendon can be utilized for tendon transfer graft to repair Achilles tendon rupture, chronic Achilles tendinopathy [6, 29].

Type III communication

In type III communication, there is a single slip extending from the FDL tendon proximally to FHL tendon distally. In this variety, a lengthy graft can be sourced from FDL tendon by including the communicating slip present between FHL and FDL tendon after severing the communication at FHL end. In such procedures, when the distal stump of FDL is sutured to the FHL tendon, a mild functional loss in little toe was reported [13]. Mao et al. have reported that type II communication was present in 0% of the observed cases. In the present study, we observed that type III communication between FHL and FDL tendon was present in 5 specimens out of 68 specimens (7.35%). This is a rare type of communication and was reported only by two authors, O'Sullivan et al. (13% of specimens) and Plaass et al. (3% of specimens), and the results of the present study were different from that of O'Sullivian et al. or Plaass et al. [20, 25]. A lengthy FDL tendon graft can be used to repair peroneus longus, peroneus brevis tendon rupture and for reconstruction surgery for flat foot deformity [21].

Type IV communication

In type IV communication, the length of the graft cannot be extended since there is no communication between the FHL and FDL tendons. LaRue et al. have reported that type III communication which is similar to type IV classification followed in the present study, where there are no communicating slips between the FHL and FDL, was present in 17% of the observed cases. In the present study, we observed that type IV communication between FHL and FDL tendon was present in 10 specimens out of 68 specimens (14.70%) and Mulier et al. reported that type IV communication between FHL and FDL was observed in 13% of all specimens which is similar to our study [9, 17].

Type V communication

In type V communication, there will be two slips connecting FHL tendon proximally to FDL tendon distally. The source of the graft will be obtained from FHL tendon and its length can be increased by including the communicating slips that are present between the FHL and FDL tendons. Edama et al. classified the communications of FHL to tendons of FDL going to various toes. Edama et al. reported that type C communication, where the FHL had connecting slips to the tendons of 2nd and 4th toe and was similar to type V classification followed in the present study, was present in 15% of the cases. In the present study, we observed that type V communication between FHL and FDL tendon was present in 6 out of 68 specimens (8.82%) and our observation is similar to the findings reported by Beger et al. (5%). This type of communication was rare and was not reported by any other authors [2, 4].

Type VI communication

In type VI communication, there will be three connecting slips, among them, two slips connect the FHL tendon proximally to FDL tendon distally, and the third slip connects the FDL tendon proximally to FHL tendon distally. This type of communication was present in none of the specimens included in the study. This is the rare type of communications documented only in a single study by Beger et al. who reported that this type of communication was present in 5% of the specimens [2].

Type VII communication

In type VII communication, there will be three connecting slips, among them, two slips connect the FDL tendon proximally to FHL tendon distally and the third slip connects the FHL tendon proximally to FDL tendon distally. In the present study, we observed that type VII communication between FHL and FDL tendon was present in 1 out of 68 specimens (1.47%) and Beger et al. reported that type VII communication was observed in 5% of all specimens and to our findings which is different from our findings [2].

In type II, VI and VII communications, the source of the graft can be from either FHL or FDL tendon since the graft obtained from either muscle will be lengthy because the graft can be lengthened by including the communication between those muscles. After obtaining the graft, the distal stump of the severed tendon is usually anchored to the nearest bone by tenodesis. Here the remaining slips of communication (distal slips) can be used to reinforce the distal stump to increase the strength of tenodesis [13].

Unusual fibers from flexor digitorum accessorius

In the present study, 2.94% (2 specimens out of 68 specimens) of the cases had an unusual communication between the fibers of flexor digitorum accessories (FDA) to the long flexor tendons of the foot, implying that FDA contributes to the flexor tendons of the toes. A similar finding was reported by Hur et al. [7].

Conclusion

Flat foot deformity can be repaired by reinforcing the posterior tibialis tendon with the help of FHL or FDL tendon transfer. In the present study, we found that type I communication was present in majority of the cases. We also found unusual slips of communication arising from flexor digitorum accessories (FDA) to long flexor tendons of foot, near the MKH. Any communications between these two muscles will influence planning the length of tendon graft. Knowledge regarding the location of MKH and point of division of FDL will aid in the planning of surgical incision of foot during grafting procedures.

Author contribution TKV: data collection. PCV: data collection. GS: manuscript writing. SSSNR: manuscript writing. VDK: manuscript writing.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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