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ORIGINAL ARTICLE

Anatomic and histological analyses of chiasma plantare and long flexor tendons of the foot on human fetuses

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Abstract

Purpose The aim of present study was to reveal slip transfers related to flexor hallucis longus (FHL) and flexor digitorum longus (FDL) by dissection and to investigate detailed structure of chiasma plantare composed of FHL–FDL tendons and quadratus plantae (QP), with precise composition of the long flexor tendons of lesser toes by histological sections in human fetuses.

Method Slip transfers related to FHL and FDL tendons were identified and the related morphometric measurements were taken with dissection in 28 formalin-fixed fetuses (25–40 weeks). Composition and restoration of chiasma plantare and long flexor tendons of lesser toes were traced histological by analyzing movements of the tissues on the sequential coronal sections in five fetuses in the third trimester. The numbers of layers constituting chiasma plantare and the muscles that formed layers were specified. Each of two to five flexor tendons arising from the chiasma plantare was analyzed regarding its formation and contribution of FHL slip.

Results Slip transfers were found as FHL slip in 86% and cross-connections in 14%. The ratios of the slip width to that of FHL and FDL tendons were found higher than in adult literature. Variance in the involvement of slip to FDL and QP, formation and layering of chiasma plantare and formation of long flexor tendons from chiasma plantare were revealed and great similarities were found with data from dissection of adult in literature.

Conclusion Slip transfers between FHL and FDL tendons, and layering properties of chiasma plantare were largely finalized during intrauterine period, while structural changes in slip seem to continue in the later stages of life, possibly by the effects of growth and usage of the extremity. In addition to individual variations, investigating the contribution of FHL slip, FDL and QP to long flexor tendons by different methods in literature is also suggested to be responsible for some diversities of our histological study.

Keywords Chiasma plantare · Long flexor tendons · Flexor hallucis longus · Flexor digitorum longus · Quadratus plantae · Fetus · Slip

Introduction

Chiasma plantare is constituted of flexor hallucis longus (FHL) and flexor digitorum longus (FDL) tendons with quadratus plantae (QP) muscle and tendon [18, 19]. There are a number of gross anatomic adult cadaver studies in the literature regarding slip which separates from FHL and participates in FDL and QP muscle tendon junction [1, 3, 7, 8, 14, 19]. Functional properties of those structures have been reported following the loss of function detected on toes after FHL and/or FDL tendon transfers and their post-operative rehabilitation periods [2, 3, 6, 14, 16, 17].

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Surgical interventions which include chiasma plantare are also frequent in the reconstruction of congenital foot deformities and cerebral palsy-related foot deformities as well [4, 5, 13, 20]. Morphological properties of muscle and tendon can change with age and usage [9, 10, 23, 24]. There is no previous study about the morphological properties of chiasma plantare in the early years of life.

In the studies of chiasma plantare, inconsistent results have been reported regarding composition of chiasma plantare and long flexor tendons of toes, and FHL slip and its contribution to two to five long flexor tendons were assessed [3, 8, 11, 12, 14, 17–19]. Identification of the tissues in adult cadavers has been performed in previous studies by blunt dissection and by applying tension to FHL and FDL tendons, and then the movement of the toes was roughly analyzed [1, 3, 14, 17–19]. When the complexity of those tissues is taken into account, it is unclear whether some varieties in data are caused by individual variations of the structures or differences in study methods.

The aims of this study were to investigate the slip transfers related to FHL and FDL tendons and their morphometric properties and to explore composition of the chiasma plantare (the FHL–FDL tendons, slip, QP muscle/tendon) in certain levels. Since fetus will allow us to make routine histological assessment of the mentioned structures in terms of its size, we also planned to identify anatomical and histological details of contributions of those structure to long flexor tendons of lesser toes.

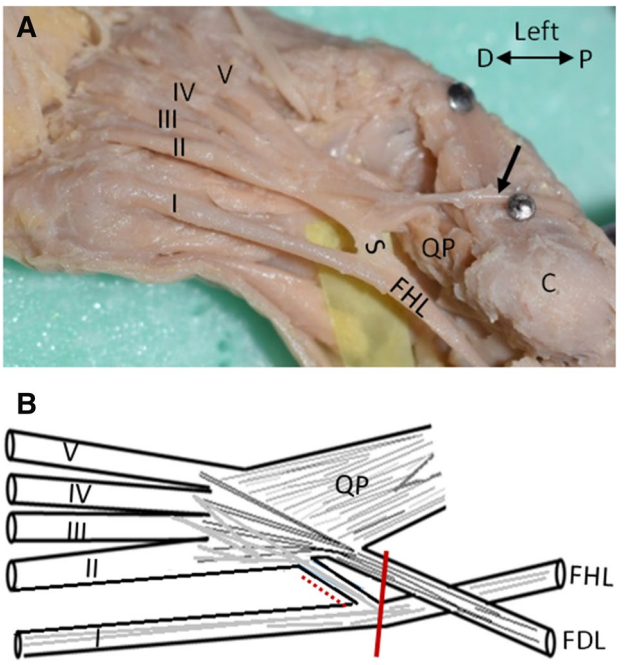

Fig. 1 **a** Photo shows the formation of chiasma plantare including FHL–FDL tendons, FHL slip, QP and long flexor tendons with lumbricals on the plantar side of left foot on 20-week-old female fetus. **b** Illustration shows the formation of chiasma plantare. Dashed red line: length of FHL slip; red line: the level of point where the width measurements of FHL and FDL tendon taken. *FHL* Flexor hallucis longus, *black arrow* Flexor digitorum longus—retracted laterally, *S* FHL slip, *QP* Quadratus plantae, *C* calcaneus, *I–V* long flexor tendons of toes, *D* distal, *P* proximal. (Color figure online)

Materials and methods

Thirty-three formalin-fixed fetuses (15 male/18 female) aged between 20 and 40 weeks, within the collection of Mersin University Faculty of Medicine Anatomy Department Laboratory, were included in the study. Plantar aponeurosis, flexor digitorum brevis, abductor hallucis and abductor digiti minimi muscles were removed by cutting from their origin in fetal samples without an apparent ankle and foot deformity. FHL–FDL tendons and QP muscle were exposed. Dissections were performed with surgical microscopes (Opmi Pico). Digital caliper with 0.01 mm precision was used for length and width measurements.

Gross anatomy

Slip transfers related to FHL and FDL tendons on soles of 28 fetuses (mean age 27.9 ± 5.1 weeks, 14 male/14 female) were examined bilaterally. Types of slip transfer between tendons were classified as the presence of slip from FHL to chiasma plantare (FHL slip), from FDL to FHL (FDL to FHL slip), cross-connections and slip absent (Fig. 1a). Morphometric measurements of FHL slip (length and width at its largest point), FHL–FDL tendons (widths of FHL and FDL tendons on proximal level of slip) were measured (Fig. 1b). Mean and standard deviation of those measurements according to gender and side were given in mm.

To assess whether the FHL slip dimensions (length and width) show any difference in the presence of a slip from FDL to FHL or not, only FHL slip cases were compared to that of cross-connection cases statistically.

By taking into account our observations during dissection, we decided to assess the possible proportional difference of slip width in fetus and adult samples. S/FHL, S/FDL and FHL/FDL ratios were calculated using data from the previous studies in adult cadavers [1, 11, 14] and our data of the fetuses.

Histological anatomy

Five fetuses (age between 33 and 36 weeks, four female/one male) with FHL slip were chosen and dissected bilaterally. FHL and FDL tendons, QP muscle and long flexor tendons of lesser toes were removed as a mass after isolating from other structures up to metatarsophalangeal joint. The mass was separated into two parts as proximal and distal.

Proximal part started from proximal of master knot of Henry up to the separation level of toe tendons, whereas distal part started from long flexor tendon separation level towards metatarsophalangeal joint.

Routine light microscopic tissue examination was applied on tissue samples by Histology and Embryology Department Laboratory. Tissues were fixed in 10% formalin solution for 24–48 h. After fixation, the routine light microscopy protocol was performed on the tissues and they were embedded in paraffin as proximal and distal parts separately. 5-µm-thick consecutive coronal slices with 1000-µm gaps in between were obtained from the paraffin blocks using a microtome from proximal to distal. The slices were stained with Masson's trichrome stain to assess connective tissues and were examined under the light microscope (Nikon Olympus BX50). Slice photos were taken with microscope and were joined on Adobe Photoshop software to obtain a complete image of the tissue. Images were queued from proximal towards distal of tissue mass and direction of tissues was examined.

Structural properties of FHL slip, the relationship of the slip with FDL and QP in chiasma plantare, and as well layering and composition of chiasma plantare were examined on slices. Following tissue mass direction on sequential slices, the joining of the slip to two to five long flexor tendons and the composition two- to five long flexor tendons of lesser toes were analyzed.

Table 1 Slip transfers related to FHL and FDL tendons regarding side and gender

Gender	Side	S from FHL to chiasma plantare *n* (%)	S from FDL to FHL *n* (%)	Cross-connection *n* (%)	S absent *n* (%)
Male	R	12 (21.4)	–	1 (1.8)	–
	L	12 (21.4)	–	1 (1.8)	–
Female	R	13 (23.2)	–	2 (3.6)	–
	L	11 (19.6)	–	4 (7.1)	–
Total *n* (%)		48 (85.7%)	–	8 (14.3%)	–

S slip, *FHL* Flexor hallucis longus, *FDL* Flexor digitorum longus, *L* left side, *R* right side

Results

Gross anatomy results

The analysis of slips between FHL and FDL tendons with gross dissection method according to side and gender is shown in Table 1. No multiple slips were observed in FHL slip cases. Morphometric properties of FHL slip (48 sides) and FDL and FHL tendons (56 sides) are shown in Table 2. Shapiro–Wilk Test was used for normality controls. When parameters of FHL slip (width and length) and FHL–FDL tendons (widths) were compared with paired *t* test, no statistically significant differences were detected between the sides ($p > 0.05$).

Width and length of FHL slips (48 sides) were measured as 1.55 ± 0.61 mm and 2.69 ± 1.18 mm, respectively. In cross-connection cases (eight sides), width and length of FHL slips were measured as 1.71 ± 0.52 mm and 3.03 ± 1.45 mm, respectively. When compared these two groups, no statistically significant difference was observed in terms of width and length ($p > 0.05$).

Mean length and width of from FDL to FHL slips in eight cross-connection cases were measured as 3.66 ± 1.69 mm (min. 1.46–max. 5.57) and 0.67 ± 0.09 mm (min. 0.50–max 0.80).

The calculated S/FHL, S/FDL and FHL/FDL ratios for the assessment of slip width changes in fetuses and adult samples are shown in Table 3. As mentioned above, the calculations were made using data from the previous studies [1, 11, 14] in adult cadavers and our data from fetuses.

Histological results

Slip properties prior to joining with chiasma plantare

Masson's trichrome stain assessment showed that the arrangement of collagen bundles of slip and FHL tendon was similar. However, during slip course towards common tissue, the fibers were moving away from each other to spread over a wider area. Slip had much more loose connective tissue than FHL tendon. Slip separated either from

Table 2 Morphometric measurements of slip, FHL and FDL tendons regarding side and gender

	S length (mm)	S width (mm)	FHL width (mm)	FDL width (mm)
Right	2.88 ± 1.39	1.58 ± 0.66	1.77 ± 0.55	1.37 ± 0.30
Left	2.61 ± 1.05	1.57 ± 0.55	1.83 ± 0.47	1.46 ± 0.34
Male	2.22 ± 0.75	1.45 ± 0.55	1.69 ± 0.36	1.38 ± 0.33
Female	3.24 ± 1.38	1.69 ± 0.63	1.90 ± 0.60	1.44 ± 0.32
Total	$\mathbf{2.74 \pm 1.22}$	$\mathbf{1.57 \pm 0.60}$	$\mathbf{1.80 \pm 0.50}$	$\mathbf{1.41 \pm 0.32}$

S slip, *FHL* Flexor hallucis longus, *FDL* Flexor digitorum longus

Table 3 Calculated width ratios of FHL slip to FHL–FDL tendons and width ratio of FHL to FDL regarding previous studies and the present study

	n	S/FHL	S/FDL	FHL/FDL
LaRue and Anctil (adult) [11]	24	2.4/6 = 0.40	2.4/5.4 = 0.44	6/5.4 = 1.11
Mao et al. (adult) [14]	64	1.79/6.42 = 0.28	1.79/7.97 = 0.22	6.42/7.97 = 0.80
Beger et al. [1]	20	2.99/5.73 = 0.52	2.99/4.57 = 0.65	5.73/4.57 = 1.25
This study (fetus)	56	**1.57/1.80 = 0.89**	**1.57/1.41 = 1.14**	**1.80/1.41 = 1.28**

Bold values indicate the ratios of this study

S slip, *FHL* Flexor hallucis longus, *FDL*Flexor digitorum longus, *n* number of cases

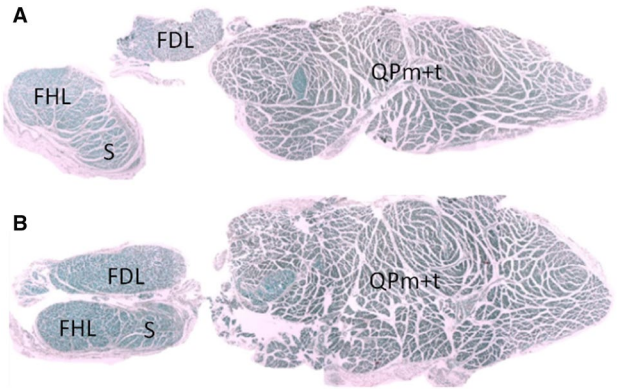

Fig. 2 FHL slip separates either from lateral aspect **(a)** or from lateral-deep aspects **(b)** of FHL tendon. *FHL* Flexor hallucis longus, *FDL* Flexor digitorum longus, *S* FHL slip, *QPm + t* Quadratus plantae muscle and tendon

the lateral aspect (in 4/10 cases) or from the lateral-deep (in 6/10 cases) aspects of FHL (Fig. 2).

Slip properties on adjoining point in chiasma plantare

The course of FHL slip to chiasma plantare, the formation of chiasma plantare and its composition and arrangement from proximal to distal are shown in Fig. 3 on histological sequential slices.

When the contribution of FHL slip to FDL and QP was assessed, FHL slip attached to QP on 9/10 sides and attached to FDL and QP in only 1 side (Fig. 4a, b). FDL always located superficial to FHL slip and QP.

Findings about chiasma plantare

Assessment of chiasma plantare layering was evaluated in two levels as proximal (in the level of attaching of FHL slip to chiasma plantare) and distal (in the level of formation of long flexor tendons of lesser toes from chiasma plantare). The detailed formation of chiasma plantare is shown in Table 4 and Fig. 3. In proximal level; chiasma plantare was found as single layered in 1/10 sides, two layered in 8/10 sides and triple layered in 1/10 sides. At distal level, it was found as single layered in 2/10 sides, two layered in 7/10 sides and triple layered in 1/10 sides (Figs. 3d–f, 4c). In accordance with the tables, dense connective tissue bundles of FHL slip, FDL and QP coursed within chiasma mass with a number of variations such as proceeding by dividing into various parts and then reunifying in various ways to form new common compact tendon masses, directing in its own direction from medial to lateral or from lateral to medial in varying degrees, and joining to only superficial or only deep or to all layers (Fig. 3).

Formation and composition of two to five long flexor tendons from chiasma plantare

- Adjoining small amount of fibers from QP, which could have only a negligible effect on both tendon volume and possible function due to their tiny size, were omitted in defining two to five long flexor tendon's composition.
- When contribution of the FHL slip to long flexor tendons of lesser toes was assessed, the slip contributed to only 2nd toe in 4/10 sides, to 2nd and 3rd toes in 5/10 sides, to 2nd–4th toes on 1/10 side. No attachment to 5th toe was seen (Tables 5, 6).
- Although there were cases with distinct three-layered formations on chiasma plantare; none of the cases showed three-layered formation on long flexor tendons (Table 6). Two layers at the origin of tendons always fused with each other in distal levels (approximately in between 4 and 6 mm).
- 2nd toe tendon was found as two layered in all cases in proximal slices. Superficial layer composed of FDL in all cases. Deep layer is composed of FHL slip in 9/10 cases and combination of FHL slip and QP in only 1 case.
- 3rd toe tendon was seen as a single-layered structure on 3/10 cases and as two layered in 7/10 cases. In single-layered cases, this tendon is composed of FDL and QP in two sides and a combination of FHL slip, FDL and QP in one side. In two-layered cases, superficial layer is composed of only FDL (3/7 sides) and a combination of FDL and QP (4/7 sides). Deep layer is composed of only FHL slip in one side, only QP in two sides and a combination of FHL slip and QP in four sides.
- 4th toe tendon was seen as a single layered in 9/10 cases with FDL. The rest one showed two-layered

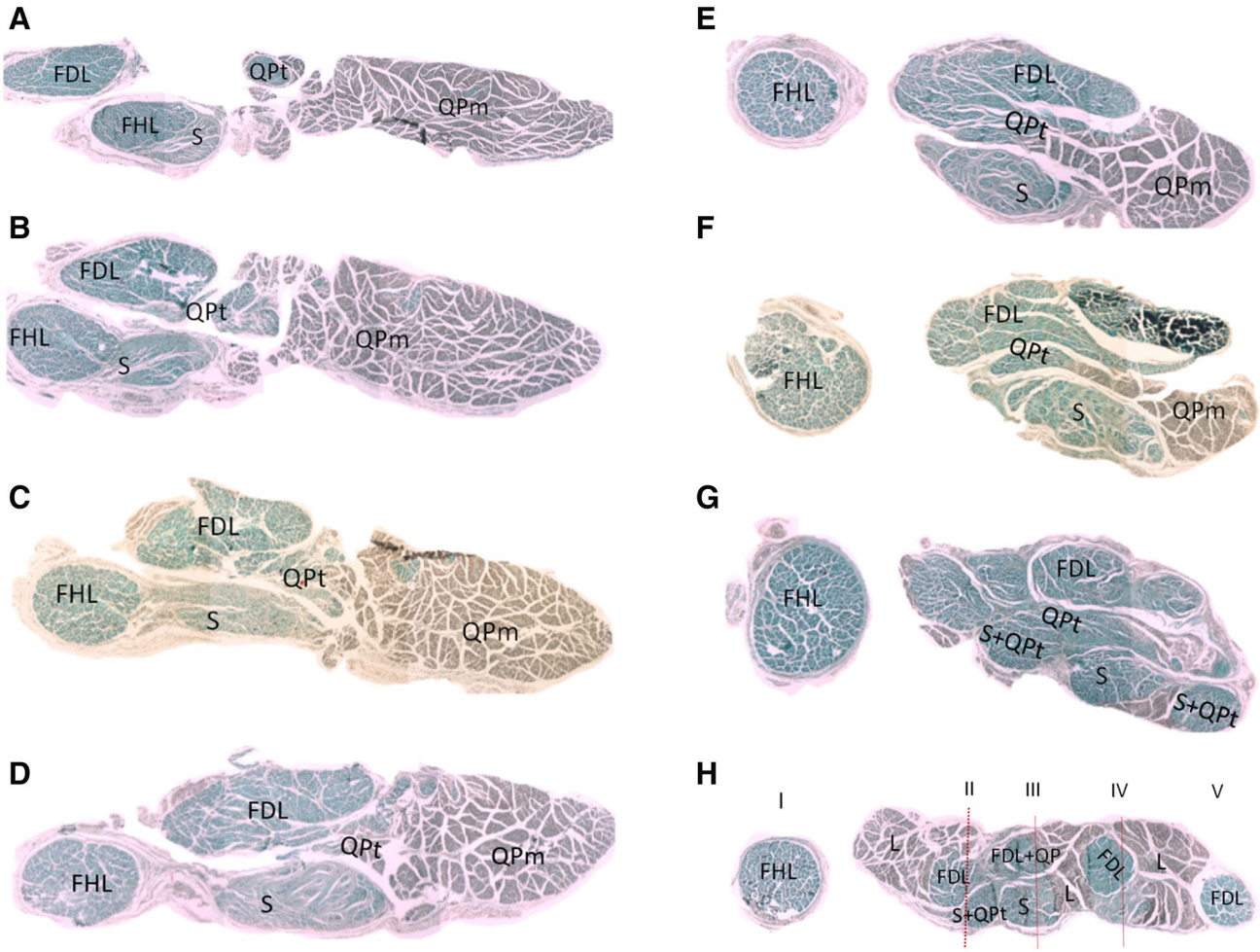

Fig. 3 The course of FHL slip, FDL and QP; the arrangement of chiasma plantare and its composition from proximal to distal levels, and formation of long flexor tendons of the plantar side of left foot of 34-week-old female fetus on histological sequential slices (not every slice). **a** FDL–FHL tendons, and QP muscle and tendon are seen as independent formations. FHL slip is ready for separation. **b** FDL courses to lateral and becomes more flat. FHL slip courses lateral to conjoin with QP muscle fibers. QP is seen as more muscle fibers and little tendineous. **c** FHL slip spreads over a wider area and has more loose connective tissue than FHL tendon. Slip conjoins with QP. FDL and QP tendon parts are closer. **d** FHL slip attaches to FHL tendon with very loose connective tissue. Slip courses laterally to conjoin already with QP. Small amount of unifying fibers of FDL and QP are seen. **e** FHL is independent. Two-layered chiasma plantare is seen in proximal level. FDL and QP are on superficial level and S is on deep layer. **f** Chiasma plantare is seen as triple layered in distal level. Superficial level composed of FDL, intermediate level composed of QP and deep level composed of S and a small amount of QP. **g** QP is seen as its tendinous form. All the components of chiasma plantare are reunified to form two to five long flexor tendons. **h** The formation of two to five long flexor tendons is almost completed. The compositions of two to five flexor tendons seem to be in various formations. Lumbricals are visible between the tendons of toes. *FHL* Flexor hallucis longus, *FDL* Flexor digitorum longus, *S* FHL slip, *QPm* Quadratus plantae muscle, *QPt* Quadratus plantae tendon, dashed red lines: numbers of one to five toes

structure where the superficial layer is composed of FDL, and the deep layer composed of FHL slip and QP.

- 5th toe tendon consisted of a single layer in all cases. It is consisted primarily of FDL in 9/10 cases and 3 of those cases had distinct QP contribution within tendons in various amounts. In only one case, 5th toe tendon was completely composed of QP (Table 6).

Discussion

The present study revealed the composition of long flexor tendons of lesser toes and chiasma plantare in detail using consecutive histological coronal slices in fetal samples (Fig. 3). Histological method was chosen to compete with very likely faults derived from the blunt dissection of such

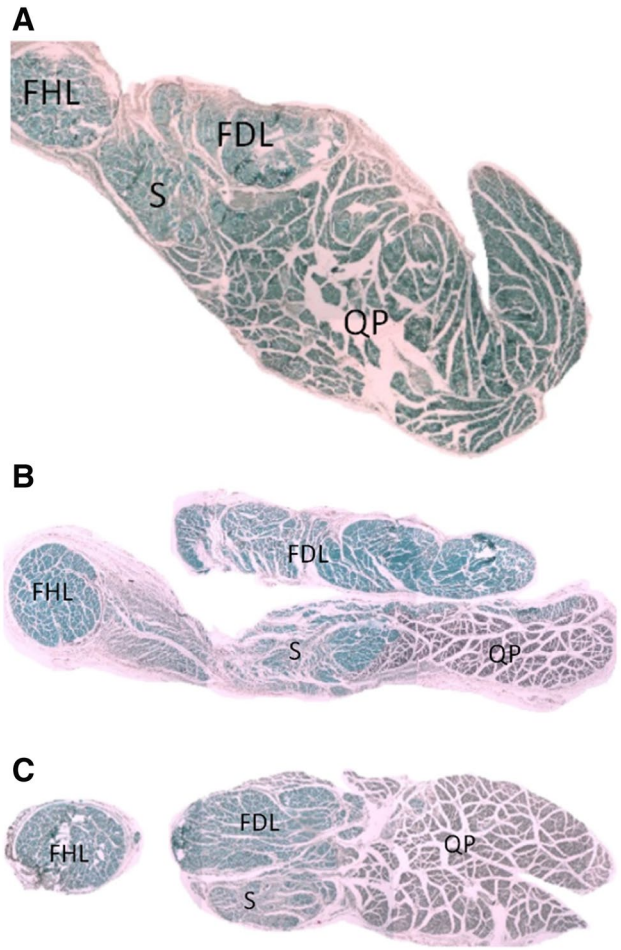

Fig. 4 Variative formations of chiasma plantare. **a** Slip attaches to FHL, FDL and QP. **b** Slip only attaches to QP. **c** Slip, FDL, and QP together form single-layered chiasma plantare. *FHL* Flexor hallucis longus, *FDL* Flexor digitorum longus, *S* FHL slip, *QP* Quadratus plantae

complex fibrous tissues during follow-up of each bundle. Fetus material was chosen for histological method as fetus because the dimension of the related structure was more suitable than adults. As opposed to adult studies, gross anatomic data on FHL and FDL tendon slips' morphometric properties we obtained from fetuses are very limited in the literature and could be beneficial in estimating the morphometric properties of those structures during the early terms of life.

Slip transfers related to FHL and FDL tendons

The fibrous band connection from FHL to chiasma plantare has been commonly called as "slip from FHL to FDL" [1, 3, 14, 18], whereas, in most of the cases (in 9/10 cases), it was observed that the FHL slip conjoined at first firmly with the QP (not to the FDL) at the proximal part of chiasma plantare, while FDL incorporated into slip–QP complex at the distal part of chiasma plantare (Table 4; Fig. 3). Accordingly, we proposed that it would be better to use the term of "slip from FHL to chiasma plantare", instead of "slip from FHL to FDL".

Although the most common slip transfer type related to FHL and FDL seen in adults has been reported to be the FHL slip to the chiasma plantare, the literature shows various rates on that subject (42–97%) [1, 3, 11, 14, 16, 18, 19]. This rate was found as 87.3% in our fetus samples. Other entities, reported in the literature such as slip from FDL to FHL (3–13%) [17, 18] and slip absent (5–17%) [11, 12, 16], were not seen in our series. Cross-connection incidence rate which has been reported as between 3 and 42% [3, 11, 14, 16–19], was found as 14.7% in our fetus samples. Our study also revealed that dimensions of FHL slip did not change in the presence of an additional slip from FDL to FHL (cross-connection cases) in fetuses ($p > 0.05$).

Previous studies provide data on morphometric properties of FHL and FDL tendons, and FHL slip in adult cadavers. Width of FHL and FDL tendons (prior to slip separation) has been reported as between 5.73–6.42 mm and 4.57–7.97 mm, respectively. Width of FHL slip has been reported to be between 1.79 and 2.99 mm [1, 11, 14]. Data on morphometric properties of those structures in fetuses we gathered are summarized in Table 2. The greater rate of slip/FHL (and FDL) in the fetuses (calculated from our data) than in the adults calculated from the data of literature [1, 11, 14] suggested the formation of the slip could change with age or usage (Table 3), (Fig. 5). Our gross anatomic observations and histological findings demonstrated that fetus slip was loose areolar tissue and more loosely configured connective tissue than FDL and FHL. This has drawn us to the suggestion that slip shape during early years of life can change to a more compact structure with less volume in later periods. As none of the fetus samples showed multiple slips from FHL to FDL, which has been seen in 10–29% adults [1, 3], it support our idea that the single, high-volume slip (Fig. 5) in early term would change into its adult form by losing the loose tissue and become multiple compact pieces.

Chiasma plantare

Chiasma plantare has been reported to be a one- to three-layered structure in the literature with gross anatomic dissections [12, 18, 19]. The varying composition of this layering was shown by examination of tissues with histological slices. Pretterklieber reported single-layered cases as 3%, two-layered cases as 69% and triple-layered cases as 28% [19]. In accordance with previous gross anatomic dissection results, histological samples also showed chiasma plantare as a one- to three-layered structure in the present study. This result

Table 4 Layering and composition of chiasma plantare in proximal and distal levels

	Side	Level	Layers	Composition
Fetus no. 1	L	P	Two layered	Superficial: FDL, Deep: S + QP
		D	Two layered	Superficial: FDL + QP, Deep: S + QP
	R	P	Single layered	FDL + S + QP
		D	Two layered	Superficial: FDL, Deep: S + QP
Fetus no. 2	L	P	Triple layered	Superficial: FDL, Intermediate: QP, Deep: S + QP
		D	Two layered	Superficial: FDL + QP, Deep: S + QP
	R	P	Two layered	Superficial: FDL + QP, Deep: S + QP
		D	Two layered	Superficial: FDL + QP, Deep: S + QP
Fetus no. 3	L	P	Two layered	Superficial: FDL, Deep: S + QP
		D	Single layered	S + FDL + QP
	R	P	Two layered	Superficial: FDL, Deep: S + QP
		D	Two layered	Superficial: FDL, Deep: S + QP
Fetus no. 4	L	P	Two layered	Superficial: FDL, Deep: S + QP
		D	Two layered	Superficial: FDL + QP, Deep: S + QP
	R	P	Two layered	Superficial: FDL, Deep: S + QP
		D	Two layered	Superficial: FDL + QP, Deep: S + QP
Fetus no. 5	L	P	Two layered	Superficial: FDL + QP, Deep: S
		D	Triple layered	Superficial: FDL, Intermediate: QP, Deep: S + QP
	R	P	Two layered	Superficial: FDL + QP, Deep: S
		D	Single layered	FDL + S + QP

P proximal level, *D* distal level, *S* slip, *FHL* flexor hallucis longus, *FDL* flexor digitorum longus, *QP* quadratus plantae tendon, *L* left side, *R* right side

Table 5 Contribution of FHL slip to two to five toes

	Side	2nd toe	3rd toe	4th toe	5th toe
Fetus no. 1	L	+			
	R	+	+		
Fetus no. 2	L	+			
	R	+	+		
Fetus no. 3	L	+			
	R	+			
Fetus no. 4	L	+	+		
	R	+	+		
Fetus no. 5	L	+	+	+	
	R	+	+		

L left side, *R* right side

indicates that the layers of chiasma plantare were almost completed just before birth.

When studies on the layering of chiasma plantare were reviewed, Lewis reported that FDL formed superficial layer, whereas FHL and QP formed deep layers [12]. On the other hand, Plaas et al. reported that FDL formed superficial, QP formed intermediate and FHL formed the deep layers [18]. Our results on two- or triple-layered cases were in accordance with the data that FDL is always found in superficial layers and, if any, intermediate layer is formed by QP [12, 18, 19].

In our study, QP contributed to superficial layer in 3/10 cases, to intermediate and deep layers in 6/10 cases in proximal level. Also, FHL slip always contributed to deep layer in accordance with previous data [19]. However, none of our two- or triple-layered cases showed FDL contribution on the intermediate layer (reported by Pretterklieber as 96%) or deep layer (reported by Pretterklieber as 36%). Additionally, FHL slip contribution to the intermediate layer or both superficial and deep layers together (reported by Pretterklieber as 4% and 21%, respectively) was not encountered in our series (Table 4).

Quadratus plantae

Quadratus plantae is thought to play an important role in chiasma plantare formation and its biomechanical effects [8, 19]. By attaching to FDL tendons, QP assists in lesser toes flexion [15, 21]. This muscle is reported to show great variance and sometimes has no contribution to 4th and 5th toes [21].

Data about the QP position within chiasma plantare and attachment to long flexor tendons is limited in the literature. Hur et al.'s anatomic study with 50 cadavers reported that QP attached to FHL slip and FDL tendon in 48 (96%) cadavers, and solely to FDL tendon in 2 (4%) cadavers. In the event of QP attachment on both FHL slip and FDL, some of the superficial muscle fibers attached to FDL and

Table 6 Layering and composition of two to five long flexor tendons at the level of separation from chiasma plantare

	Side	2nd toe	3rd toe	4th toe	5th toe
Fetus no. 1	L	Two layered Superficial: FDL Deep: S	Single layered FDL + QP	Single layered FDL + QP	Single layered FDL
	R	Two layered Superficial: FDL Deep: S	Two layered Superficial: FDL Deep: S + QP	Single layered FDL + QP	Single layered FDL
Fetus no. 2	L	Two layered Superficial: FDL Deep: S	Single layered FDL + QP	Single layered FDL + QP	Single layered FDL + QP
	R	Two layered Superficial: FDL Deep: S	Two layered Superficial: FDL + QP Deep: S + QP	Single layered FDL + QP	Single layered FDL
Fetus no. 3	L	Two layered Superficial: FDL Deep: S	Two layered Superficial: FDL Deep: QP	Single layered FDL + QP	Single layered FDL
	R	Two layered Superficial: FDL Deep: S	Two layered Superficial: FDL + QP Deep: QP	Single layered FDL + QP	Single layered FDL
Fetus no. 4	L	Two layered Superficial: FDL Deep: S	Two layered Superficial: FDL + QP Deep: S + QP	Single layered FDL + QP	Single layered FDL + QP
	R	Two layered Superficial: FDL Deep: S	Two layered Superficial: FDL Deep: S + QP	Single layered FDL + QP	Single layered QP
Fetus no. 5	L	Two layered Superficial: FDL Deep: S + QP	Two layered Superficial: FDL + QP Deep: S	Two layered Superficial: FDL Deep: S + QP	Single layered FDL
	R	Two layered Superficial: FDL Deep: S	Single layered FDL + S + QP	Single layered FDL + QP	Single layered FDL + QP

S slip, *FHL* Flexor hallucis longus, *FDL* Flexor digitorum longus, *QP* Quadratus plantae tendon, *R* right side, *L* left side

a large number of them attached to the lateral side of FHL slip (in accordance with our study findings) [8]. Our findings indicate that in all cases the slip firmly attached to the QP from the proximal part of the chiasma plantare, whereas the slip–FDL relationship is weaker in the proximal part and that the fusion is more distal level of the chiasma plantare (Table 6).

When 2nd–5th long flexor tendon compositions were assessed in terms of QP contribution (Table 5) with examination of histological sequential slices of tissues, it was seen that QP attached to 3rd and 4th toes in all cases, and rarely to 2nd (1/10 sides) and 5th toe tendons (4/10 sides). Plaas et al. reported that QP attached to all small toes in his dissection study [18]. Lewis reported that QP attached to 2nd and 3rd toe tendons in 4/18 cadavers and to 2nd–4th toe tendons in 14 out of 18 cadavers [12]. Finally, Pretterklieber reported that QP attached to 2nd–4th tendons in all cases, and to the 5th tendon in half of the cases [19]. Histological findings showed us that QP contribution to 2nd toe was not as much as reported previously in the literature. In gross anatomic dissections, it becomes difficult to follow the fibers' direction after the point of bundles' adjoining point. In such materials, course of connective tissue masses can be followed using histological sequential sections more properly. Accordingly, we suggest that some diversity between our results and the previous data may be caused by different methods rather than materials (fetus or adult).

Participation of FHL slip to two to five toes

In the literature, the rates for the contribution of FHL slip to 2nd–5th toes have been reported for every variable; for 2nd toe as 8–71% (mean 35%), for 2nd–3rd toes as 29–64%, for 2nd–4th toes as 0–28% and 2nd–5th toes as < 1% [3, 8, 12, 14, 18, 19, 22]. In the present study, FHL slip was found to support only 2nd toe in 40%, 2nd and 3rd toes in 50%, and 2nd–4th toes in 10%. No case where it supports 5th toe was seen (Table 4).

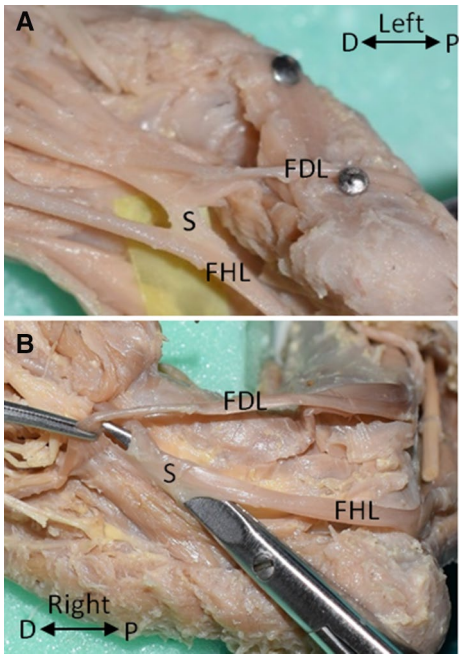

Fig. 5 Single (**a**) and high-volume (**b**) slips from FHL to chiasma plantare are seen in photos. *FHL* Flexor hallucis longus, *FDL* Flexor digitorum longus, *S* FHL slip

Formation of two to five long flexor tendons

We focused on the composition of two to five long flexor tendons with muscle and tendon orientation analysis and found that long flexor tendons were formed by FDL tendon, FHL slip and QP. However, the composition of toes showed a variance, as shown in Table 6; 2nd toe is composed of either by FDL with slip or FDL, slip with QP. The 3rd and 4th toe is composed of either by FDL with QP or a combination of slip, FDL and QP. Finally, the 5th toe is composed of either by only FDL, only QP or FDL with QP combination. Even though our study was mostly in accordance with Pretterklieber's results [19], the main differences were that the QP tendon mass had only small contribution to the tendon of 2nd and 5th toes (Table 3).

Conclusion

The fact that fetal samples show a great similarity with adult samples in slip transfer types related to FHL and FDL tendons and layering properties of chiasma plantare shows us that this structuring is mainly finalized during intrauterine period. In addition, the greater proportional dimension of the slip in fetus (S/FHL, S/FDL) than the adults can be explained by the argument that the structure of slip is affected by growth and/or usage of extremities. However, further studies are necessary to clearly define the term of life in which slip dimension reach to their adult form.

One of the implications of our findings is that the FHL slip conjoined firmly with the QP, instead of the FDL. Therefore, it is suggested that the term "slip from FHL to chiasma plantare" would be more feasible than the widely used term "slip from FHL to FDL".

The variations seen in contribution of FHL slip, FDL and QP to long flexor tendons can be due to both individual variations and the differences in study methods. The main factors that make the correct determination of which tendon reaches to which toe a challenge were defined as the great variations seen in dense connective tissue bundles' course within chiasma mass (from medial-to-lateral, from lateral-to-medial, joining on only superficial, only deep, or both two/three layers) and differences in sources (from FHL slip, FDL and/or QP), joining on various configurations and levels and then forming new common compact tendon masses during their courses.

Author contributions Ö Elvan: project development, data management, data analysis, manuscript writing, editing. O Beger: project development, data management, data analysis. Mİ Karagül: data management, data analysis, manuscript writing. D Uzmansel: project development, data analysis, editing. NŞ Yılmaz: data management, data analysis, editing. Z Kurtoğlu Olgunus: project development, data analysis, manuscript writing, editing.

Compliance with ethical standards

Conflict of interest Authors declared no conflict of interest.

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