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Anatomical Study of the Compositions and Internal Connections of the Chiasma Plantare (Master Knot of Henry): Exploring Its Possible Clinical Impact



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ABSTRACT

The purposes of this study were to integrate the types of interconnecting fibers among components of the chiasma plantare and to deduce their flexion actions. The chiasma plantare and the long flexor tendons in 52 cadaveric feet (26 left feet and 25 right feet) were dissected and removed via gross anatomic dissection. The connections among the flexor digitorum longus (FDL), flexor hallucis longus (FHL), and quadratus plantae (QP) were then classified and analyzed. The connection between the FHL and FDL was type I in 43 (86%) cases, type III in 2 (4%) cases, and type V in 5 (10%) cases, with the FHL manipulating the first through third toes and the FDL manipulating the first through the fifth toes. The shape of the QP in 28 (56%) cases exhibited a 2-headed QP, and in 22 (44%) cases, a medial-headed QP. The composition of the chiasma plantare was 2 layers in 28 (56%) cases and 3 layers in 22 (44%) cases: 9 (18%) cases were type a, 2 (4%) cases were type b₁, and 1 (2%) case each was classified as type b₂ and b₃. The FHL controlled the second toe in 10 (20%) cases; both the second and third toes in 27 (54%) cases; and the second, third, and fourth toes in 13 (26%) cases. The QP manipulated the third and fourth toes in all cases, the second toe in 38 (76%) cases, and the fifth toe in 11 (22%) cases. These data suggest that such variations might result from tendon transfer. In conclusion, we considered the FDL to be more advanced for the recovery of both the ankle and the forefoot based on this study.

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Transfer of the flexor hallucis longus (FHL) and flexor digitorum longus (FDL) tendons is routinely used in the reconstructive treatment of missed or neglected Achilles tendon rupture to substitute for the functional role of the Achilles tendon. This approach is also used to restore the function of a deficient or dysfunctional posterior tibialis tendon, which consistently results in adult acquired flatfoot deformity (AAFD) (1–5). Interestingly, various surgical techniques for harvesting these tendons had been described in many reports. The tendons are available to

be harvested in the posteromedial hindfoot, the forefoot medial malleolus, the chiasma plantaria, and even the interphalangeal joint (2,3,6–10). Furthermore, because of the many incisions involved in the transfer of the FHL and FDL tendons, multiple surgical methods had been used. However, regardless of which surgical technique is used in the treatment of foot and ankle diseases, it is essential to search for the optimal method for harvesting tendons, which would prevent complications, such as injuries to nerves and the vasculature, dysfunction of the great toe, FHL weakness, and decreased distal phalangeal pressure (7–9,11). Therefore, accurate classification of the interconnections among the FHL, FDL, and QP and their variations is of vital importance. The knot of Henry, which is also called the chiasma plantare, exists in the mid-plantar foot and is a signal of the combination of the FHL, FDL, and QP. There is high variability in the interconnections of these 3 components with the lesser long flexor tendons in the mid-foot to distal-foot (12,13). In addition, several reports have demonstrated that there are many types of connections between the FHL and FDL, which contribute more variations to the chiasma plantare (12–15). Subsequently, the consistent details of the long flexor tendons of the 5 toes arising from these 3

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tendons have been demonstrated by few authors; these reports do not sufficiently classify the variations of the chiasma plantare. Only in Pretertklieber's (13) description, reported in the past few years, can we acquire a relatively detailed classification of the interconnections among the FHL, FDL, and QP.

In the present study, the connections between the FHL and FDL and the structure of their fibers connecting with the QP, as well as the branches of these 3 tendons to each of the 5 long flexor tendons, were analyzed and described, along with the shape of the QP. Furthermore, the present results were used to integrate and classify the composition of the chiasma plantare and the connections between the FHL and FDL. In addition, the flexion actions of the toes were deduced and classified according to the toe dedication of each long flexor tendon comprehensively controlled by the assembly of the FHL, FDL, and QP. Based on the anatomic dissection and classification just described, we study explore and discuss use of the superior tendon for transfer.

Methods

Specimens

We used 50 legs from 25 cadavers of Asian donors (mean age, 82.2 ± 8 years; 10 feet from women and 40 feet from men) that had been switched to alcohol after placement in 10% formalin. One fresh-frozen cadaver was used to identify the dedication of FDL and FHL. It was about how they flex further long flexor of toes, which was shown in our video to clarify their impact of flexion. All of these individuals had donated their bodies to medical education and research at the Department of Anatomy, Yanbian University. In addition to the informed consent of the deceased individuals, the study was approved by the Ethics Committee of the Medical College of Yanbian University. None of legs showed conspicuous signs of surgery around the regions of the chiasma plantare and 5 long flexor tendons. Additionally, there were no deformities on the lower legs or feet.

Dissection

The feet were dissected via medial and plantar incisions, and the skin and subcutaneous tissue was removed from the plantar, lateral, and medial retromalleolar regions. The tarsal tunnel was dissected, and the anatomic structures were identified. Plantar aponeurosis was identified and excised. The crural fascia in the retromalleolar regions was removed and flapped proximally. The tendons of the deep flexors of the toes, together with the lumbricals, the superficial plantar muscles, and the plantar vessels and nerves, were exposed and detached meticulously. The flexor digitorum brevis was cut at the metatarsophalangeal joints; the muscle fibers of the flexor digitorum brevis, abductor hallucis, and abductor digiti minimi were detached from their origin in the region of the calcaneus. The neurovascular bundle was removed cautiously in the deep plantar region of each foot. We pulled the FDL and FHL to demonstrate the dedication of 2 tendons in flexing the long flexor tendons of the toes. The FHL, FDL, and their musculotendinous connections with the QP, which compose the chiasma plantare, were revealed, along with 5 long flexor tendons. In this way, we have access to analyse the interconnections of the structures of the chiasma plantare more obviously. The flexor retinaculum was removed to open the tarsal tunnel, exposing the tibial nerve, posterior tibial artery, and FHL and FDL tendons. After side identification, 5 long flexor tendons were cut from the distal phalanges of the toes, as well as the lumbricals from the dorsal digital expansion. After detachment of the QP from its origins and separation of the FHL and FDL tendons from the tarsal tunnel, the entire chiasma plantare was released from the sole of the foot in 25 cadavers (50 specimens).

Analysis

The number of layers constituting the chiasma plantare was counted and classified, and the formations of the layers were specified. The shape of the QP were differentiated by different muscle belly interconnections and its origins, as well as the connection of the QP with the FDL to the distal long flexor tendons. In addition, according to previous reports (12–15), the combinations of the FHL and FDL and the branches of the FHL and distal FDL to each toe were classified. All data were analyzed using IBM SPSS Statistics 20 (IBM, Armonk, NY) for the descriptive analysis. The cross-sectional area of the FHL and FDL through the plantar region of the foot and laterally through the ankle was interrupted. We compared the cross section of the tendon to an ellipse and used a Vernier caliper to measure the long axis and the short axis to obtain the cross-sectional area, with the area estimated by using GraphPad Prism 4.0 (GraphPad Software, San Diego, CA, USA). For all qualitative data, statistical analysis was restricted to frequency calculations in GraphPad Prism 4.0. The photographs and videos were produced with a Canon EOS 5D Mark III (Canon Inc., Tokyo, Japan) and video edited with the use of Corel VideoStudio X10 (Corel, Ottawa, Canada).

Results

Shape of the QP

As reported by Hur et al. (16), the shape of the QP was classified into 3 types: 2 headed, medial headed, and lateral headed. In our study, we found 2 QP shape types: 2 headed and medial headed. No lateral-headed QP specimens were identified during our dissection. In 22 (44%) specimens, the medial-headed type was identified and denoted as M. In 28 (56%) specimens, the 2-headed type was identified and denoted as ML. We found that approximately 8 specimens had tendinous or aponeurotic tissue in or among the QP muscle; of these, 6 were medial headed and 2 were 2 headed (Figs. 1 and 2). The 2-headed type had 2 isoforms in our study: 1 head lying on the lateral aspect and 1 head lying on the medial aspect. The lateral head was identified arising from the lateral border of the inferior calcaneal surface, and the medial head was identified arising from the medial concave surface of the calcaneus. They join together and insert into FDL (Fig. 3). Combined with earlier investigations (16–18), it could be concluded that the QP with 2 heads must be composed of 2 muscle bellies with or without tendinous or aponeurotic tissue. Most medial-head types had 1 muscle belly; no lateral-head types were identified in this study. The shape of the muscle bellies of the QP were classified as type A, having a single muscle belly (Fig. 4) (16 specimens [32%]); type B, having 2 muscle bellies with tendinous tissue covering the medial (8 specimens [16%]) (Fig. 5), type C, having 2 muscle bellies interconnecting with each other (Figs. 3 and 6) (17 specimens [34%]); and type D, having 2 muscle bellies interconnecting and covering FDL (9 specimens [18%]) (Fig. 7).

Cross-Sectional Areas of the FHL and the FDL

Based on our calculations, we obtained a cross-sectional area of 0.0395 ± 0.0104 cm² (mean) for the FHL and 0.0307 ± 0.0897 cm² for the FDL. There was no sufficiently significant difference between the 2 tendons (p > .05).

Connections Between the FHL and the FDL

During our investigation, we identified 5 precedents that were available to >1 branch between the FHL and the FDL, 1 of which involved 5 branches covered by soft issue; the others involved 2 branches from the FHL to the FDL. These 2 branches were distinguished from the superficial, middle, and deep layers of the FHL tendon in the plantar view (Fig. 8). Most of the 45 (90%) specimens showed connection of the FHL to the FDL by only 1 FHL branch, which constituted the long flexors of the toes. Then, the 2 precedents for connecting the FDL to the FHL were assessed (Fig. 9).

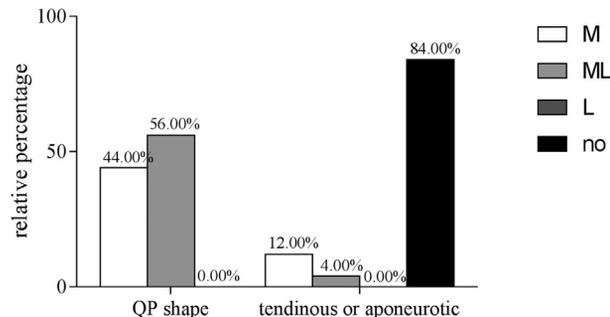


Fig. 1. Shape of the QP and tendinous or aponeurotic tissue observed in the QP region.

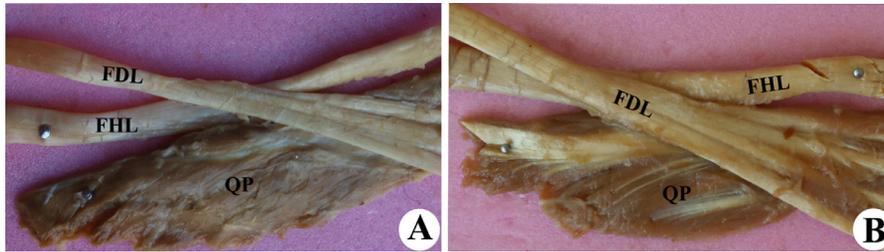


Fig. 2. Plantar view of the chiasma plantare. (A) The QP muscle shows a medial-headed shape. (B) The QP muscle shows a medial-headed shape and contains tendinous tissue.

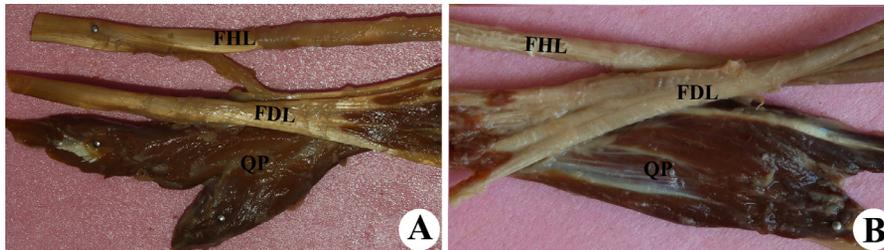


Fig. 3. The plantar view of the chiasma plantare. (A) The QP muscle shows a 2-headed shape. (B) The QP muscle shows a 2-headed shape but is connected to more than 2 parts.

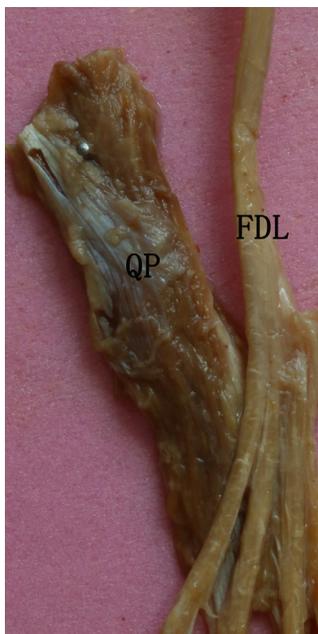


Fig. 4. Illustration of the shape of QP muscle belly of Type A: one single muscle belly along with FDL.

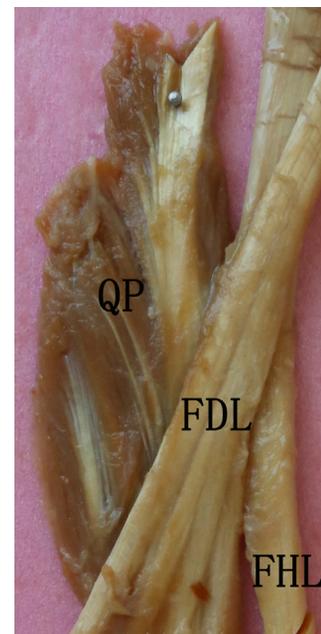


Fig. 5. Illustration of the shape of QP muscle bellies of Type B who has 2 muscle bellies with tendinous covering.

According to a report by Plaass et al. (14), connections between the FHL and FDL can be classified as type I, a single slip from the FHL to the FDL; type II, a single slip crossing from the FDL to the FHL; type III, an interconnection between the FHL and the FDL; type IV, no connection; and type V, a double connection, which was shown in an earlier report (15). The results of our study according to this classification system are shown in Fig. 10. We found 43 type 1 (86%) specimens, 2 type 3 (4%) specimens, and 5 type 5 (10%) specimens.

In the results of the various interconnections of the FHL tendon and the FDL tendon, as well as the QP, when we pulled the tendons, the curvature movement of each long tendon of the toes was apparent (Video). When we pulled the FHL tendon in the tarsal tunnel where the FHL

muscle and its tendon connected, the first toe flexed together with second and third toes. When we were pulling the FDL tendon, the second to fifth toes flexed obviously and the first toe spontaneously removed. Pulling the proximal branch from the FHL to the FDL, we identified the first toe and the second and third toes flexed conspicuously, which demonstrated the function of interconnections between the FHL and FDL tendons to dedicate the long flexor of the toes.

Composition of the Chiasma Plantare

As a result of various variants of the interconnections, which was also called assembly, in this study, the composition of the chiasma

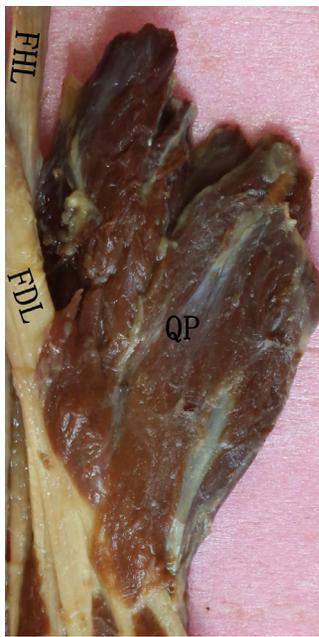


Fig. 6. Illustration of the shape of QP muscle bellies.



Fig. 7. Illustration of the shape of QP muscle bellies covering FDL.

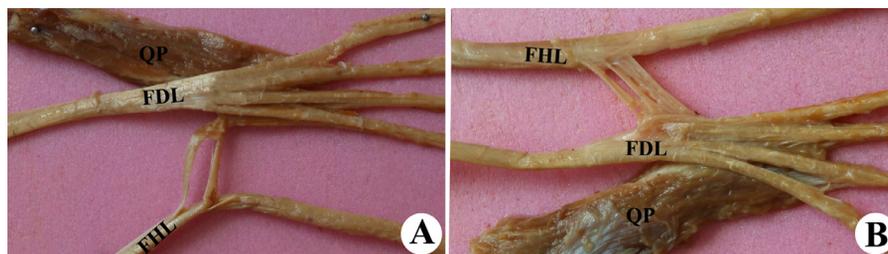


Fig. 8. (A) The chiasma plantare from a right foot. There are 2 branches from the FHL to the FDL. (B) The chiasma plantare from a left foot. There are approximately 5 tendinous or soft tissue branches connecting the FHL and FDL. The images are in the plantare view.

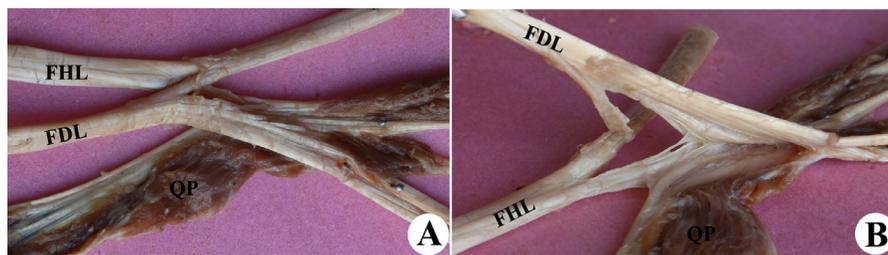


Fig. 9. Two-layered chiasma plantare in the left foot: the plantare view. (A) The FDL is in the superficial layer. (B) The FDL branch goes into the FHL, and the FHL branch enters the tendinous fibers of the QP, which cross to the deep layer. The FDL branch links with the FHL, and the FHL branch links with the FDL. Type III (interconnection between the FDL and FHL).

plantare was classified into many types. In all specimens, the chiasma plantare consisted of the FHL and FDL tendons and the muscular or tendinous fibers of the QP. Two chiasma plantare types were identified and classified by the number of layers: 2 layers were observed in 37 (74%) cases, and 3 layers were observed in 13 (26%) cases. The following classifications were identified in the plantare view.

We found 2 forms among the 2-layered chiasma plantare. In one form, the surface of the chiasma plantare is covered by FDL in the plantare view, and the FHL branch interconnects with the QP to form the deep layer; this form was observed in 28 (56%) specimens and is designated as FDL-QP+FHL (Fig. 9). In the other form, the connection between the QP and FDL formed the superficial layer, whereas the FHL

branch crosses the QP to form the deep layer; this form was observed in 9 (18%) specimens and is designated as QP + FDL-QP + FHL (Fig. 11).

When examining the influence of the various FHL branches, we identified 2 types of 3-layered chiasma plantare and 3 isoforms of type b. Type a is the most common type and was observed in 9 (18%) cases; the surface layer consists of the FDL, the middle layer is composed of the interconnection between the FDL and QP, and the QP and a branch of the FHL combine to form the deep layer. This type was designated as FDL-QP + FDL-QP + FHL (Fig. 12). Type b was identified as 3 isoforms based on various branches of the FHL. Type b₁ was observed in 2 (4%) cases and was designated as FDL + FHLU-QP + FDL-QP + FHLD (FHLU: the superficial branch of FHL; FHLD: the lower branch of FHL). The

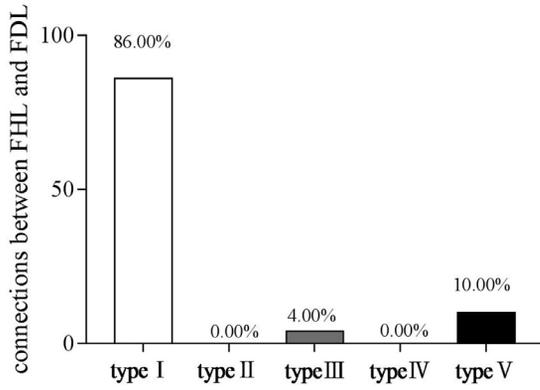


Fig. 10. Respective connections between the FHL and FDL.

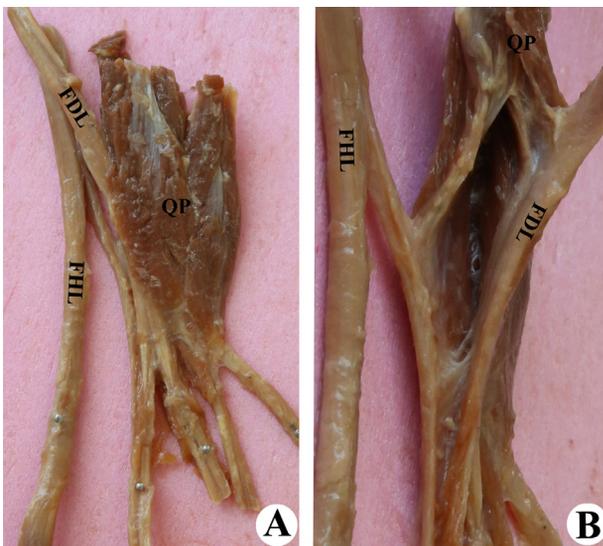


Fig. 11. Two-layered chiasma plantare from the right foot: the plantar view. (A) The QP is in the superficial layer. (B) The superficial layer consists of the QP and FDL, while the deep layer consists of an FHL branch interconnected with the QP.

superficial branch of the FHL and the FDL assemble to form the superficial layer in the plantar view. The FDL and QP assemble to form the middle layer. The deep layer is assembled by the deep branch of the FHL and the QP (Fig. 13). Type b₂ was observed in 1 (2%) case and was designated as FDL-QP + FDL + FHLU-QP + FHL D. As in type a, the superficial layer consists of the FDL. In contrast, the FDL, QP, and superficial branch of the FHL assemble to form the middle layer; furthermore, the QP and the other branch of the FHL form the deep layer (Fig. 14). Type b₃ was

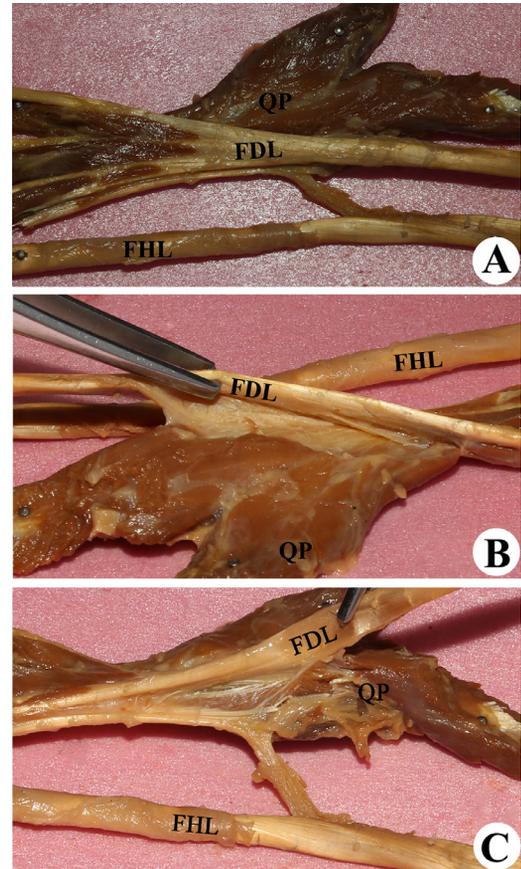


Fig. 12. Three-layered chiasma plantare in a left foot: the plantar view. (A, C) FDL is the superficial layer of the chiasma plantare. (B) The FDL and QP are in the middle layer, and a branch of the FHL and the QP form the deep layer.

observed in 1 (2%) case and was designated as FDL + FHLU-FDL + FHL D-FDL + QP. As in type b₁, the superficial branch and the lateral branch of the FHL were assembled to the FDL, which formed the surface and middle layers, and the FDL and QP assembled to form the deep layer (Fig. 15).

Interestingly, we found that the FDL was involved in formation of the superficial layer in all cases (100%), and among the 2-layered chiasma plantare, 9 (24.32%) cases exhibited QP involvement in the superficial layer and connection with the FDL to assemble the first layer in the plantar view. Among the 3-layered chiasma plantare, the FDL was identified in all middle layers, and the QP was in all layers except for the middle (92.31%). Additionally, the deep layer involved the QP and FHL (Fig. 16).

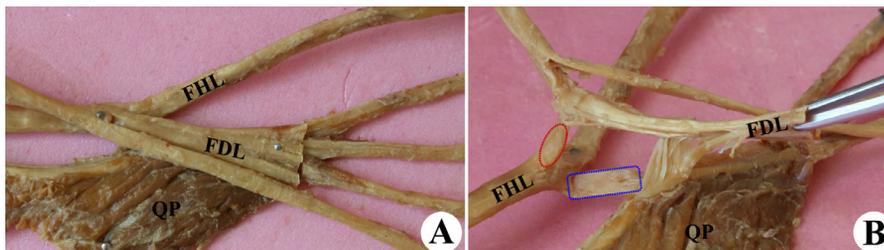


Fig. 13. Three-layered chiasma plantare in the left foot: the plantar view. (A) The superficial layer consists of the FDL (B) The superficial layer is composed of the FDL and one branch of the FHL (red). The middle consists of the FDL and QP. The deep layer includes the other branch of the FHL (blue) and the QP.

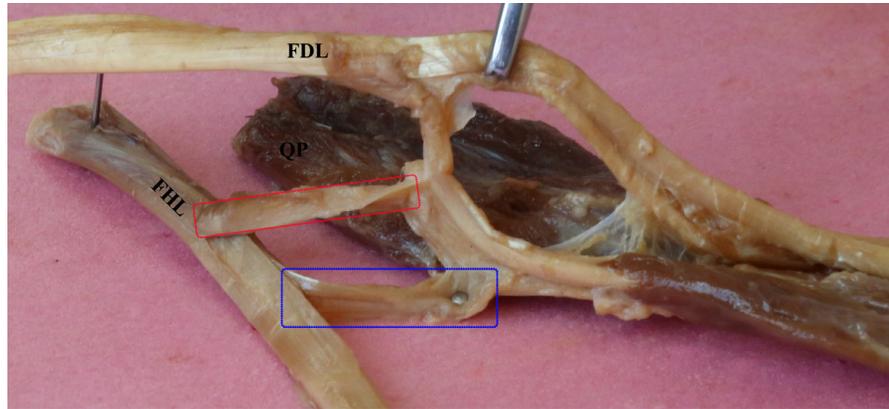


Fig. 14. Three-layered chiasma plantare in a right foot. The FDL is the superficial layer; the QP, FDL, and a branch of the FHL (red) compose the middle layer; the QP and a branch of the FHL (blue) form the deep layer.

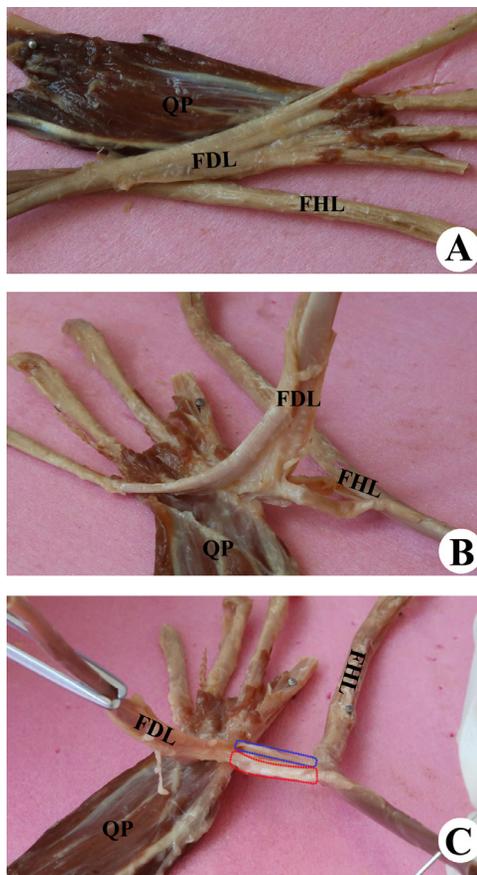


Fig. 15. Three-layered chiasma plantare in the right foot: the plantar view. (A) The superficial layer consists of the FDL. (B) The superficial layer consists of the FDL combined with a branch of the FHL (red). The middle layer consists of the interconnection of the FDL and the other branch of the FHL (blue). (C) The deep layer consists of the QP and FDL.

Formations of the Long Flexor Tendons of the Toes

Because of the interconnections among the FHL, FDL, and QP, which have been named the chiasma plantare, branches of the FHL are involved in controlling the lateral long flexor tendons of the 5 toes (Video). The branches of FHL tissue assemble with the long flexor tendons to reach each toe. For our dissections, FHL tendon branches could connect to the second, third, fourth, or fifth toe. Only the second toe accounted for 10 (20%) cases, and both the second and third toes

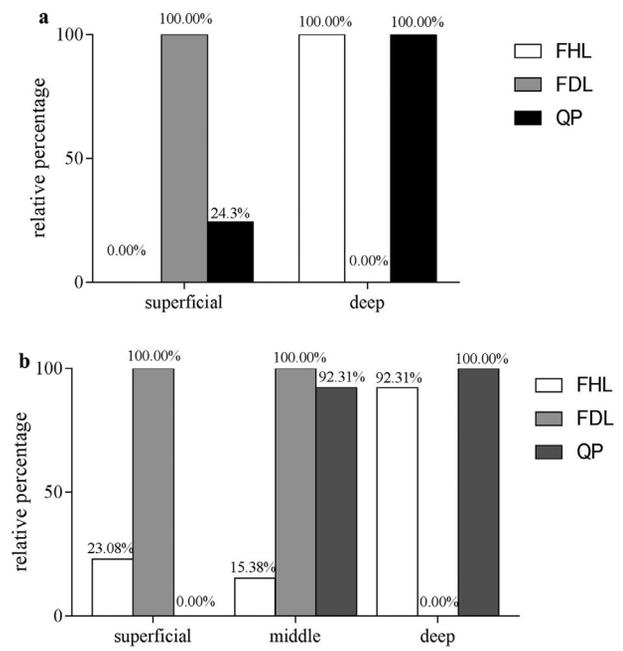


Fig. 16. (A) Structures involved in the superficial and deep layers of the 2-layered chiasma plantare. (B) Structures involved in the superficial, middle and deep layers of the 3-layered chiasma plantare.

accounted for 27 (54%) cases; the second, third, and fourth toes together accounted for 13 (26%) cases, whereas we did not identify any connections of an FHL branch with respect to the fifth toe in our specimens (Fig. 17).

According to the demonstration of the shape and composition of the QP over the chiasma plantare, the QP has dedicated muscle and tendinous tissue to long flexor tendons to control the forefoot, such as the interphalangeal joints or toes. We grouped QP control into 4 types: type a, assembling the second, third, and fourth toes, accounts for 27 (54%) cases; type b, assembling the third and fourth toes, accounts for 12 (24%) cases; type c, assembling all but the first toe, was found in 8 (16%) cases; and type d, assembling the third, fourth, and fifth toes, was found in 3 (6%) cases (Fig. 18). Notably, if the QP did not control the fifth toe, the only factor associated with the fifth toe was the FDL tendon in the superficial layer of the chiasma plantare. Furthermore, if the QP was in the superficial layer of the chiasma plantare, all long flexor tendons and toes except the first were controlled by the QP.

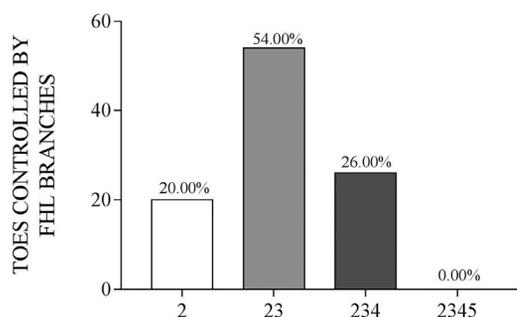


Fig. 17. FHL tendon branches assembling with the long flexor tendons of the second, third, fourth, and fifth toes.

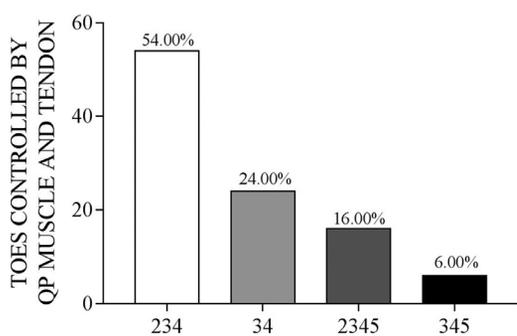


Fig. 18. Muscle and tendons involved in the long flexor tendons of the toes.

Table 1
Frequency of toe formations

	FHL	FDL	QP
Toe 1	50	2	0
Toe 2	50	50	38
Toe 3	40	50	50
Toe 4	13	50	50
Toe 5	0	50	11

Abbreviations: FDL, flexor digitorum longus; FHL, flexor hallucis longus; QP, quadratus plantae.

Table 2
Various assembly of 5 tendons

Toe	FHL	FDL	QP	FHL + FDL	FHL + FDL + QP	FDL + QP	Sum
First	48	0	0	2	0	0	50
Second	0	0	0	12	38	0	50
Third	0	0	0	0	40	10	50
Fourth	0	0	0	0	13	37	50
Fifth	0	39	0	0	0	11	50

Abbreviations: FDL, flexor digitorum longus; FHL, flexor hallucis longus; QP, quadratus plantae.

The frequency of the involvement of the 3 structures composing the chiasma plantare in the long flexor tendons of the toes is shown in Table 1. On the whole, every FDL controlled the second through fifth toes, but in 2 cases, the FDL branch crossed over to the FHL, which formed an interconnection, leading to domination of the first toe. The FHL tendon was involved with the long flexor tendons of the first toe. With a branch of the FHL assembled with the chiasma plantare, the FHL was involved with the second toe in all cases, the third toe in 40 (80%) cases, the fourth toe in 13 (26%) cases, and never with fifth toe. The QP was involved with the third and fourth toes in all cases. In 38 (76%) cases, the QP was involved with the second toe. The QP controlled the fifth toe in 11 (22%) cases and did not control the first toe in any cases.

The frequency of the assembly of the lateral long flexor tendons of the toes is shown in Table 2. The first toe was totally controlled by the FHL tendon in 48 cases, but 2 cases showed FDL slip assembly. In 12 cases, the second toe was controlled by the FHL and FDL and by all 3 structures in 38 cases. The third toe was controlled by all members in 40 cases and by the FDL and QP in 10 cases. The fourth toe as unique as the third toe; it was controlled by all members in 13 cases and the FDL and QP in 37 cases. Specifically, in 39 cases, the fifth toe was controlled only by the FDL, but in 11 cases, it was controlled by the FDL and QP.

Discussion

Shape of the QP

During our dissection of the chiasma plantare, we determined that the QP has access to the flexor action of the forefoot zone and we identified various shapes of QP tissue, including muscle, tendinous, or aponeurotic tissue. We classified the shape of muscle bellies and their connection. In the description of Hur et al (16), 2-headed, medial-headed, and lateral-headed QP muscles were identified. Pretterklieber's (17) recent investigation into the human QP muscle sufficiently classified the number of heads, points of origin, and type of insertion of the QP. Insertion of the flexor digitorum accessorius longus onto the QP was mentioned by both these authors, but it occurred rarely. In all, 56% of the QP cases showed 2 heads and were designated as ML (medial-lateral), and 44% of the QP cases showed 1 head on the calcaneus and were designated as M (medial). No lateral-headed QP specimens were identified in our study, as they have been in earlier reports (17,19). A QP with 2 heads is a more common type than a QP with 1 head, as described by Pretterklieber (17) and Hur et al (16). Interestingly, in the composition of the chiasma plantare, 3 types of QP insertions have been described: muscular, tendinous, and aponeurotic, as classified by Pretterklieber (17). We affirmed muscular insertions in 42 (84%) cases and tendinous or aponeurotic insertions in 8 (16%) cases. The flexor digitorum accessorius longus was not identified during our dissection. In Nakanowatari's et al. (18) exploration, they confirmed that the medial and lateral heads of the QP were accountable in flexion movements of the lateral 4 toes. They had identified that the medial head of QP has assisted second-toe flexion and the lateral head has aided to flex all 4 lateral toes. This investigation confirmed the function of the QP with the lateral toes, which might play a role in the substitute of FDL tendons when it is transferred.

Connections Between the FHL and FDL

Based on investigations of the connections between the FHL and FDL, 5 types of connections have been clearly described. Type I is the most common; types III and V are less common but have been previously reported, as well as described in this study. Although type IV has been defined for a long time, it has never been reported. Type II is also rarely described and only appears in the description of O'Sullivan et al (12). Among our cases, we observed type I in 86%, type III in 4%, and type V in 10%. Interestingly, type III, which had defined the interconnections between the FHL and the FDL, had been identified new subtypes by other report. In Turkish individuals, crossed connection was demonstrated: 2 slip from FHL to FDL and one slip from FDL to FHL, and 2 slip from FDL to FHL and one slip from FHL to FDL (20). There were no new types noted in our study; possibly because the ethnicity of all our donors was Asian.

In the past 10 decades, various explorations of the connections between the FHL and FDL have been demonstrated, all of which showed cases of 1 or more tendinous slips from the FHL to the FDL and the bidirectional crossover of both tendons. A few studies have described the interconnections of the FHL and FDL, in which the FDL branches to the

FHL and the FHL branches to FDL (12–15,20). Notably, in our study, a string of soft tissue covering the branch from the FHL to the FDL exhibited clear tendinous slips dividing the tissue into several portions.

Structure of the Chiasma Plantare and the Long Flexor Tendons of the Toes

Assembly is the foundation of mechanical technology. As a result of the complex composition of the chiasma plantare, we aimed to identify the various structural assemblies and significant impacts of the FHL, FDL, and QP. We primarily used the term “assembly” and its verb in our study to describe the identified role of each structure.

The complete formation of the chiasma plantare has rarely been described; only 1-, 2-, and 3-layered specimens were sufficiently classified in Pretterklieber's (13) report. The author demonstrated that the chiasma plantare were composed of interconnections among the FHL, FDL, and QP, including tendons and the muscular and tendinous fibers of the QP, which are involved in the lateral flexor action of toes in the forefoot. The 1-, 2-, and 3-layered specimens of the chiasma plantare were also clearly manifested. In this study, we dissected 2-layered types in 37 cases and 3-layered types in 13 cases, but no 1-layered types were found, as they were in Pretterklieber's (13) report. To classify the layers of the chiasma plantare, we first released the whole tissue from the cadavers in a deliberate manner. The superficial layer was identified as composed of the FDL in both types, and the QP was involved in the deep layer. We found 2 types of the 2-layered specimens and designated them as FDL-QP + FHL and QP + FDL-QP + FHL. The types of 3-layered specimens were designated as follows: FDL-QP + FDL-QP + FHL, FDL + FHLU-QP + FDL-QP + FHL, FDL-QP + FDL + FHLU-QP + FHL, and FDL + FHLU-FDL + FHL-QP + FDL-QP + FHL. The FDL + FHLU-QP + FDL-QP + FHL and FDL + FHLU-FDL + FHL-QP + FDL-QP + FHL types found in our study are new. In addition, the 3-layered type of the chiasma plantare in this study was shown to be affected by the connections of the FHL branches with the chiasma plantare, which additionally augmented the types of layers. Furthermore, the QP muscle was considered in Pretterklieber's (13) report as well as in our study, and our results show that QP plays an essential role in the functional characteristics and composition of the chiasma plantare.

In the present study, 2-layered the chiasma plantare (74%) was the most frequent type. The FDL was always in the superficial layer, and the FHL always branched to the QP to assemble the deep layer together. The QP was somewhat involved in the superficial layer (18%), whereas the FHL was not identified in the superficial layer and the FDL was not present in the deep layer. In the chiasma plantare with 3 layers, called the 3-layered type and previously reported by Pretterklieber (13), the FDL was mostly involved in the superficial layer, and in some cases, branches of the FHL were also present in the superficial layer (8%). Differing from early reports, we found no cases in which the QP muscle was lying in the superficial layer of the 3-layered chiasma plantare. In the middle layer, the FDL was always involved, with a few odd branches of the FHL present in some cases as well (15.38%). QP accounted for 92.31% of the samples in the middle layer. Interconnections of the FDL and QP were present in 92.31% of the middle layers. Clearly, as in Pretterklieber's (13) study, the QP and FHL were very involved in the deep layer. Otherwise, no FDL was identified in the deep layer in our study, which was different from earlier studies (13). These differences might be due to the number of samples or differences in the species and/or environment.

As generally acknowledged, the anatomy of the FHL tendon controls the first metatarsophalangeal joint, which provides the final lift-off power for working, running, and jumping (19). The assembly of the FHL tendon with other tissues combined with the chiasma plantare allows it to contribute to the flexor function of the long flexor tendons of the toes. As mentioned in earlier reports, branches of the FHL tendon play a significant role in assembling the FDL and QP tissue (13,16,17). The FHL

always controls the second toe. The number of reinforced tendons in the third toe was counted to the second level. Yet, the FHL has no remarkable effects on the fourth or fifth toe (13–15). In this study, we found that the FHL tendon controlled the first and second toes in all cases, the third toe in approximately 80% of cases, the fourth toe in 26% of cases, and never the fifth toe. The composition of the chiasma plantare was classified as the FHL joining the FDL and QP, which clearly controlled the long flexor tendons of the toes. Hence, the action of all 4 lateral flexor tendons was indirectly controlled by the assembly of the FHL tendon in the chiasma plantare. Also, the contribution of the assembly of the chiasma plantare FHL tendon could subconsciously manipulate all toes.

The FDL tendon, which was present in the superficial layer of the chiasma plantare in this and other studies (13), fundamentally influences the 4 interphalangeal joints and lateral long flexor tendons to the toes. However, FDL branching to the FHL allowing control of the first metatarsophalangeal joint was demonstrated in only 2 cases in this study and in 1 case in an earlier report (20). Conspicuous was the significant function of FHL in daily activity; power or gait was difficult to replace by FDL or even assembly of the chiasma plantare. Because of the special interconnections among the FHL, FDL, and QP, variable structures of the long flexor tendons to each toe have been identified by various authors from different countries and using specimens of different species, which might directly explain the various discrepancies among the results.

In the formation of the chiasma plantare, the QP is involved as well as the 5 long flexor tendons, which are also assembled with the FHL and FDL, especially the latter. According to the summary launched by Pretterklieber's (13) description and our study, the QP is more frequently dedicated to the third and fourth toes than to the others. In contrast, the QP seldom controls the first toe. What worth to mention was in the muscle elasticity investigation launched by Tatsuya (18), who demonstrated the assistance of 2 heads of QP muscle play role in plantarflexion of the lesser toe (13,18). The results from that exploration suggested that the medial head of QP assisted second-toe flexion, and the lateral head affiliated the flexion of all 4 lateral toes (13,16–18). Regarding the fifth toe, our study found that when the QP is in the superficial layer of the chiasma plantare, the QP must control the fifth toe, and the opposite cannot occur. However, in Tatsuya et al's ultrasound real-time tissue elastography measurements on volunteers, the QP assisted in flexing all lesser toes, and it might be concluded that the QP may replace the function of the transferred FDL and the assembly of the chiasma plantare makes it capable.

Similarly, assembly of the 3 major components of the chiasma plantare in the dorsal region of the foot that interact with each other in the medial dorsal foot and lateral forefoot, or even the toes, has been described in previous studies, but the assembled structures were first defined in our study. Regardless of which members are included in the assembly of the chiasma plantare, we definitely consider the resulting interactions to be sufficient to allow each biomechanical function involved in tendon and toe flexion, based on various studies of the interconnections among the tendons of the dorsal foot.

Utility of the FHL and FDL Tendons in Clinical Treatment Which Is More Advantageous?

FHL and FDL transfers, which are good uses of the tendons' anatomical superiority, are widely used in the clinical treatment of dysfunction or injury in the dorsal ankle, such as chronic Achilles tendon rupture, posterior tibial tendon dysfunction causing acquired flatfoot deformity, and concomitant peroneal tendon tears (2,4–6,21–23). Prominently, to guarantee the active and biomechanical functions of the ankle and a normal gait postoperatively, various methods have been developed and applied. To reconstruct the function of the Achilles tendon after chronic

injury, in which the 2 ends of the ruptured tendon have atrophied, surgeons have explored and attempted many surgical methods that ensure both the functional rebuilding and the use of the recipient and donor. Based on the length of the tendon gap, different surgical methods are generally used: reconstruction with the FHL, FDL, or peroneus brevis with or without dermal tissue matrix (10,21); V-Y advancement with or without the transfer (24) or augmentation of the FHL or local turn-down flap from the gastrocnemius aponeurosis or FHL muscle (25–29); and synthetic graft augmentation (30–32). In addition, to preserve the basic action and strength of the foot, other surgical augmentation methods for transferring the FDL or FHL have been used, such as FHL transfer with or without tenodesis in the knot of Henry (7,9,11,21) and FHL tendon transfer into the calcaneus using interference screw fixation or using the calcaneus tunnel to transport the FDL or FHL tendons (30,31,33,34). With the progressive development of endoscopic techniques, FHL tendoscopy has become equally used in such transfers and reconstructions (35–38). Nevertheless, there were few reports describing which one would be the better choice of transfer from the perspective of postoperation.

In general, any surgical intervention that alters the normal position of these muscles or tendons is likely to diminish normal function and compromise efficient locomotion (35,39). From an anatomical perspective, tenodesis is a questionable technique after transfer of the FHL or FDL, which requires double incisions. The benefits of double incisions for harvesting FHL tendons include the available space for tenodesis and adequate FHL or FDL tendon length. Shortcomings of this approach include the risk of neurovascular injury and the additional medial incision along the foot (7–9,11). Single-incision techniques result in significant weakness in hallux interphalangeal flexion strength; however, patients with a deficiency in the flexion of the greater or lesser toes during daily living rarely comply (7,8). Transfer of the FHL tendon with or without other augmentation to cure dorsal ankle dysfunction and foot diseases has been widely demonstrated and used in clinical treatment, similar to the other surgical techniques. Furthermore, FHL tendon transfer has been well received by most surgeons and patients, and the issue of compliance has rarely been mentioned (1–3,6–11,21,22,24,26–28). FDL tendon transfer, which is also performed to correct the dysfunction of other tendons and approach the FHL in the posterior ankle, was recently shown to be an alternative for the more traditionally used FHL tendon transfer, especially in more active and younger individuals (3–5). FDL transfer was emphasized to have comparable clinical and functional outcomes, with few complications, donor site morbidities, and gait disturbances. Subsequently, from the biomechanical perspective, after FHL and FDL transfer surgery with a single incision, a significant decrease from the intact state occurs in flexion force for the great and lesser toes, respectively (8). A significant ability to reconstruct flexion force in the great and lesser toes was shown via a tenodesis technique over transfer alone for the FHL and FDL, but the flexion force remained less than normal (40,41). Prominently, there was no statistical significance between the cross-sectional area of the FHL and FDL tendons measured in our exploration. Hence, we had no precise evidence with which to prove which tendon is superior. But based on our anatomical dissection procedure, we'd rather conceive that FDL might be better choice for transfer, with less power loss of the first metatarsophalangeal joint which was acknowledged as bearing the key force of walking and standing.

Recent reports demonstrate that the most acceptable method for tendon transfer was use of the FHL, which was a proven technique during either open surgery or an endoscopic technique; fewer used the FDL. In the perspective of length and incision chosen, FHL was first considered with or without the augmentation of other muscle tissue, especially the intensively contracting Achilles tendon (8). Surgeons used 1 or 2 incisions to obtain an adequate length of FHL tendon in the Mark Henry knot or dorsal first metatarsophalangeal joint. Likewise, as a

result of FDL constituting Mark Henry knot with FHL, FDL possesses similar length for transferring and could be a substitution or augmentation for other augmentation techniques. However, there was no significant difference between the 2 approaches regarding reconstruction of the dorsal ankle joint but not for foot impact. Therefore, it would be an influential approach that focuses on postoperative functional changes in flexion and forefoot power. As acknowledged widely, FHL plays a significant role in gait and normal arch structure that struggle to maintain physiological and morphological characteristics, balancing gait and undertaking weight from the whole body on toe-off when walking (16). Anatomical research indicated that the assistance of FDL to flex the first toe was infrequent (Video) in our study as well, so the function of FHL to flex the first toe could not be perfectly remedied when it is transferred. Accordingly, we can conceive the impact of FHL on part of forefoot would better not be replaced. In the normal position, the FDL tendon plays a role in flexion of lesser tendons of the toes together with the component of chiasma plantare mentioned earlier. QP had access to play assistant role in flexion of lesser flexor tendons of toes and with less bearing the strength of whole body in lateral forefoot, which supported our hypothesis that FDL tendon transfer might be better than FHL tendon transfer on the perspective of postoperation (18). Thus, we considered FDL was the preferred choice of tendon transfer.

In conclusion, the composition and interconnections of the chiasma plantare was able to replace the functions of the FHL or FDL after transfer. The function of the first metatarsophalangeal joint and the interphalangeal joints of the 4 toes would be lost but would not have an obvious influence on daily activities. For the choice of the FHL or FDL tendon to transfer, we believe that FDL was more advanced for recovery of both ankle and forefoot based on this work for long-term impact on function. We had no objective situation to collect real clinical examples, so the limitation of this study was lack of clinical verification to support our perspective, but anatomical dissection did so remarkably. We have sincere expectation that surgeons can provide us with clinical evidence to verify our hypothesis. For ethical difference and the limitation of the number of donated individuals, our donors were Asian, which probably entails occasional differences but enriches the data of this field. Precise knowledge of the anatomy of the chiasma plantare in the plantar foot is essential to facilitate the choice of incision for tendon harvesting, estimate and explore personal operation methods by anatomical characteristics, reduce morbidity and predict possible postoperative functional losses to reduce, or thoroughly avoid dysfunction and additional injury. Thus, more investigations on the composition of the chiasma plantare are needed to identify personalized surgical approaches based on the anatomical structure of every patient. Further studies using imaging techniques would support this target.

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Supplementary Materials

Supplementary material associated with this article can be found in the online version at <https://doi.org/10.1053/j.jfas.2018.09.032>.

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