

## Research Article

## Anatomical study of toe flexion by flexor hallucis longus



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## ARTICLE INFO

## Article history:

Received 8 September 2015

Received in revised form 9 November 2015

Accepted 10 November 2015

## Keywords:

Tendinous slip

Classification of interconnection

Tendon transfer

## ABSTRACT

Because connections exist between the flexor hallucis longus (FHL) and flexor digitorum longus (FDL), the FHL is surmised to exert a flexion action on the lesser toes, but this has not been studied quantitatively. The objectives of this study have thus been to clarify the types of FHL and FDL connections and branching, and to deduce the toe flexion actions of the FHL. One hundred legs from 55 cadavers were used for the study, with FHLs and FDLs harvested from the plantar aspect of the foot, and connections and branches classified. Image-analysis software was then used to analyze cross-sectional areas (CSAs) of each tendon, and the proportion of FHL was calculated in relation to flexor tendons of each toe. Type I (single slip from FHL to FDL tendon) was seen in 86 legs (86%), Type II (crossed connection) in 3 legs (3%), and Type III (single slip from FDL to FHL tendon) or Type IV (no connection between muscles) in 0 legs (0%). In addition, Type V (double slip from FHL to FDL tendon) was seen in 11 legs (11%), representing a new type not recorded in previous classifications. In terms of the various flexor tendons, the proportion of FHL showing tendons to toes 2 and 3 was high, at approximately 50–70%. Consequently, considering the branching type and proportion of CSA, the FHL was conjectured to not only act to flex the hallux, but also play a significant role in the flexion of toes 2 and 3. These results offer useful information for future clarification of the functional roles of tendinous slips from the FHL.

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## 1. Introduction

Tendon transfer of the flexor digitorum longus muscle (FHL) and flexor digitorum longus muscle (FDL) is widely used as a treatment for Achilles tendinitis, rupture of the Achilles tendon, and dysfunction of the tibialis posterior muscle (DiPaola and Raikin, 2007; Schon et al., 2013; Wegryz et al., 2010). For this reason, a large number of anatomical studies have been conducted from the standpoint of harvesting tendons that are sufficiently long, preventing complications such as injury to nerves and arteries, and preventing postoperative deterioration in the function of the site from which the tendon is harvested.

Because of the functional aspect and relationship to the incision site, many of the anatomical studies involving the FHL have focused on the relationship (tendon connections) between the FHL and FDL (LaRue and Anctil, 2006; Mao et al., 2014; Martin, 1964; Mulier et al., 2007; O'Sullivan et al., 2005; Wapner et al., 1994). Over 80% of such studies agree that the FHL and FDL connect with each other, but opinions differ regarding the type of connections and branching to the lesser toes. Various reports have cited markedly different numbers of specimens (16–85 legs), and ethnic differences have also been suggested to exist (Mao et al., 2014).

With respect to the functional role, anatomically speaking, the tendinous slip of the FHL is considered as an agonist for the flexion of toe 2 (Mao et al., 2014). Moreover, this slip has also been reported to play an important role in toe-off when walking (Hur et al., 2011). However, because connections exist between the FHL and FDL, the FHL is surmised to exert a flexion action on the lesser toes, but this has not yet been quantified.

Tendons are believed to be enlarged in step with muscle enlargement resulting from the burden imposed by training, and numerous

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reports have described the relationship between muscle and tendon size (Elliott, 1965; Kongsgaard et al., 2005, 2007; Sommer, 1987). Based on these reports, a strong relationship is thought to exist between the cross-sectional areas (CSAs) of muscles and tendons. Consequently, although the sites differ, flexion action of the FHL on the lesser toes might be estimated by measuring CSA of the FHL branches to the lesser toes.

Given the above, the present research aimed to clarify the types of FHL and FDL connections and branching using 100 legs from cadavers, and to estimate the flexion action of FHL on the lesser toes by measuring CSAs of tendons inserting from the FHL.

The present study was based on the hypothesis that the FHL not only acts to flex the hallux, but also plays a significant role in the flexion of toes 2 and 3.

## 2. Materials and methods

### 2.1. Cadavers

This study used 100 legs from 55 cadavers (mean age,  $80.1 \pm 11$  years; 61 sides from men, 39 sides from women), which had been switched to alcohol after placement in 10% formalin. No legs showed signs of major previous surgery around the foot or ankle, or relevant deformities. All study protocols were approved by the ethics committee at our institution (#131206).

### 2.2. Procedure

The feet were dissected by medial and plantar incisions, removing the plantar skin. The tarsal tunnel was dissected and the anatomical structures identified. The plantar aponeurosis was meticulously dissected from the flexor digitorum brevis and removed; then the flexor digitorum brevis, flexor hallucis brevis, and abductor hallucis were dissected and lifted to the distal side. The FHL, FDL, quadratus plantae, and lumbricalis pedis muscles were then harvested (Fig. 1). Referring to earlier reports (O'Sullivan et al., 2005; Plaass et al., 2013), connections between the FHL and FDL were classified as: Type I, single slip from FHL to FDL tendon; Type II, crossed connection; Type III, single slip from FDL to FHL tendon; or Type IV, no connection between muscles. Type V was

defined as a double slip from FHL to FDL tendon, representing a new type not recorded in previous classifications. Again referring to earlier reports (O'Sullivan et al., 2005; Plaass et al., 2013), FHL branches to the lesser toes were also classified as: Type A, connection from FHL to toe 2; Type B, connection from FHL to toes 2 and 3; Type C, connection from FHL to toes 2–4; or Type D, connection to all lesser toes.

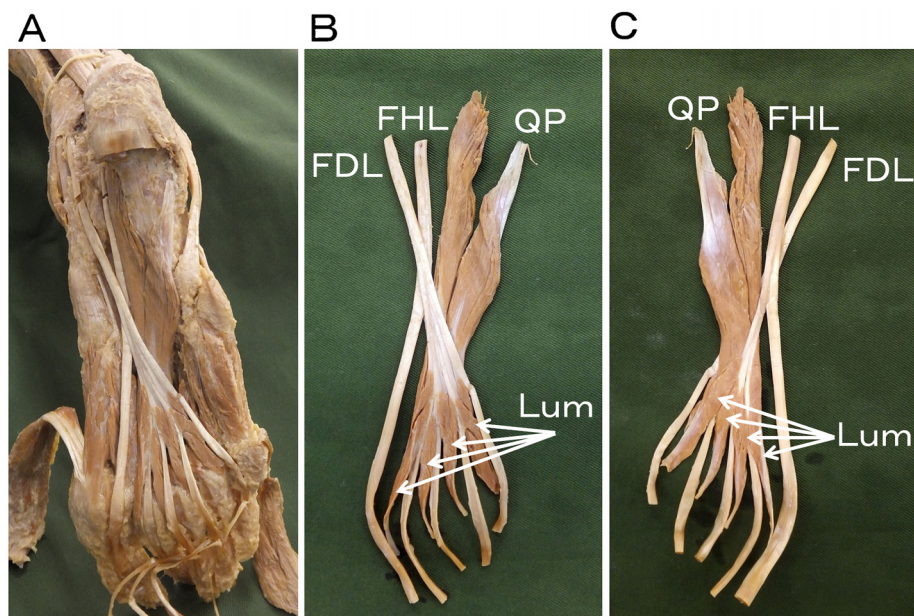
Next, the FHL was separated from the quadratus plantae muscle. Very strong adhesion was seen between these fascicles, which had to be carefully teased apart (Fig. 2A). Afterward, FHL was separated from the tendons extending toward the other toes, which also had to be carefully teased apart (Fig. 2B). Next, at the part of the FHL branching into the tendon extending toward the hallux and the tendons extending toward the other toes, transverse section of the various tendons was performed. Transverse section of the flexor tendons (tendons at which the FDL, quadratus plantae muscle and FHL are joined) of the toes was similarly performed at the proximal phalanges of toes 2–4 (Fig. 2B). The various cross-sections were then photographed using a digital camera (Finepix F600EXR; Fujifilm, Tokyo, Japan). Image analysis software (ImageJ, National Institutes of Health, Bethesda, MD) was used to calculate CSAs (Fig. 3). The proportion of branching to each tendon was then calculated, using the total sum of CSAs of the FHL branching to the hallux and lesser toes as the total CSA of the FHL. The proportion of FHL in relation to flexor tendons of each toe was also calculated. In some cases, the FHL branched to the lumbricalis pedis muscle, but these branching tendons were extremely thin (Fig. 4) and were therefore excluded from CSA measurements.

### 2.3. Statistical analysis

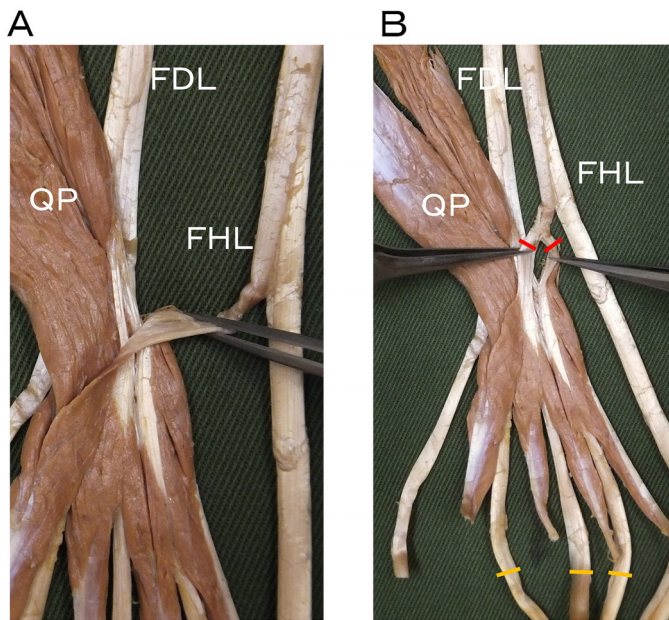
Type comparisons between males and females and between left and right sides were performed using the chi-square test, with 5% taken as the level of statistical significance.

## 3. Results

Type I was found in 86 legs (86%), Type II in 3 legs (3%) and Types III and IV in 0 legs (0%). Type V (double slip from FHL to FDL tendon)



**Fig. 1.** Method of dissection. Right foot, posterior view. The plantar skin and plantar aponeurosis were removed (A), and the FDL, FDL, QP and Lum were extracted (B). (C) The back of panel (B). FHL, flexor hallucis longus; FDL, flexor digitorum longus muscle; QP, plantar quadratus muscle; Lum, lumbricalis muscle.



**Fig. 2.** Method of dissection. Right foot, posterior view. FHL was separated from the plantar quadratus muscle (A), and FHL was separated from the tendons extending toward the other toes (B). And the FHL tendon was cut in cross-section at the location where it branches to the hallux and other toes (B; red line). Flexor tendons to other toes were further cross-sectioned at the proximal phalanges of digits 2–4 (B; yellow line). FHL, flexor hallucis longus; FDL, flexor digitorum longus muscle; QP, plantar quadratus muscle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

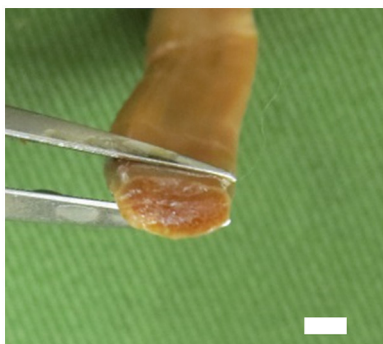
was seen in 11 legs (11%), representing a new type not recorded in previous classifications (O'Sullivan et al., 2005; Plaass et al., 2013) (Fig. 5).

Type A accounted for 38 cases (38%), Type B for 54 cases (54%) and Type C for 8 cases (8%). Among Type A and B cases, branching was to the lumbricalis pedis muscle in 17 cases (17%). No Type D cases were identified (Fig. 6).

No significant sex-based differences were apparent. In differences between left and right legs, both legs were able to be measured for 45 cadavers (54 legs from 27 male cadavers and 36 legs from 18 female cadavers). No significant differences were thus evident (Table 1).

The proportion of FHL branching to each toe is shown in Table 2.

The proportion of FHL with respect to flexor tendons to each toe is shown in Table 3. Among the proportions of FHL with respect to the various flexor tendons, the proportion of FHL to toes 2 and 3 was high, approximately 50–70%.



**Fig. 3.** Method of calculate CSA. Right FHL. Red line: calculate area. CSA, cross-sectional area. Scale bar: 5 mm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 4.** Connections from FHL to the lumbrical muscle. Right foot, posterior view. Red arrow: connections from FHL to the lumbrical muscle. FHL, flexor hallucis longus; FDL, flexor digitorum longus muscle; Lum, lumbrical muscle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 1**  
Sex and left-right difference.

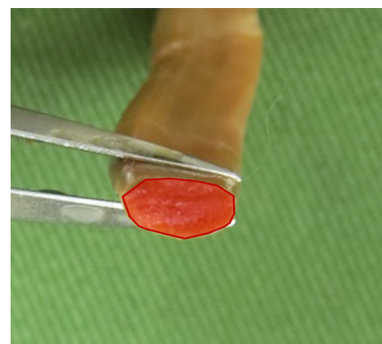
| Type   | Male (%) / female (%) (n = 100) | Left (%) / right (%) (n = 90) |
|--------|---------------------------------|-------------------------------|
| Type 1 | 23 (38%) / 15 (38%)             | 16 (36%) / 16 (36%)           |
| Type 2 | 31 (51%) / 23 (59%)             | 26 (58%) / 24 (53%)           |
| Type 3 | 7 (11%) / 1 (3%)                | 3 (6.7%) / 5 (11%)            |

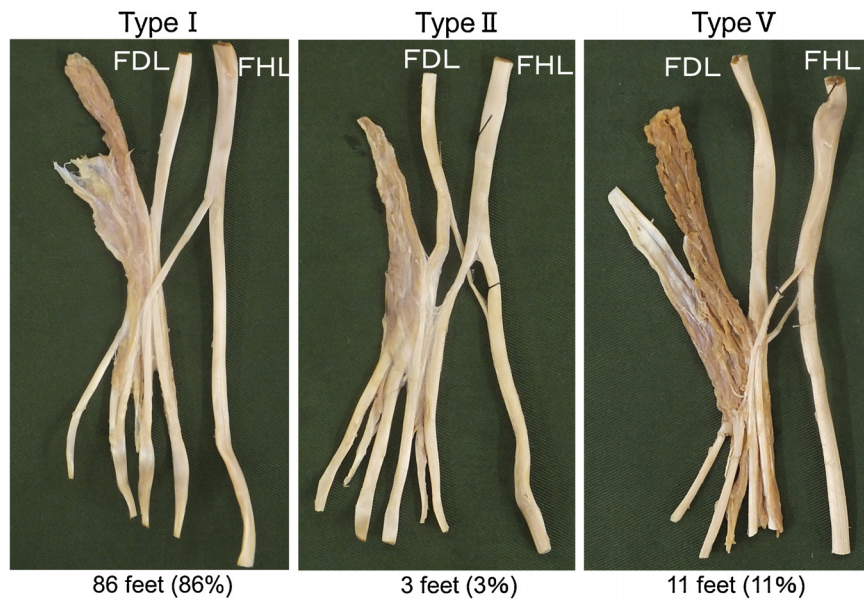
In differences between left and right legs, we were able to measure both legs from 45 cadavers (54 legs from 27 male cadavers and 36 legs from 18 female cadavers).

**Table 2**  
Proportion of FHLs branching to each toe.

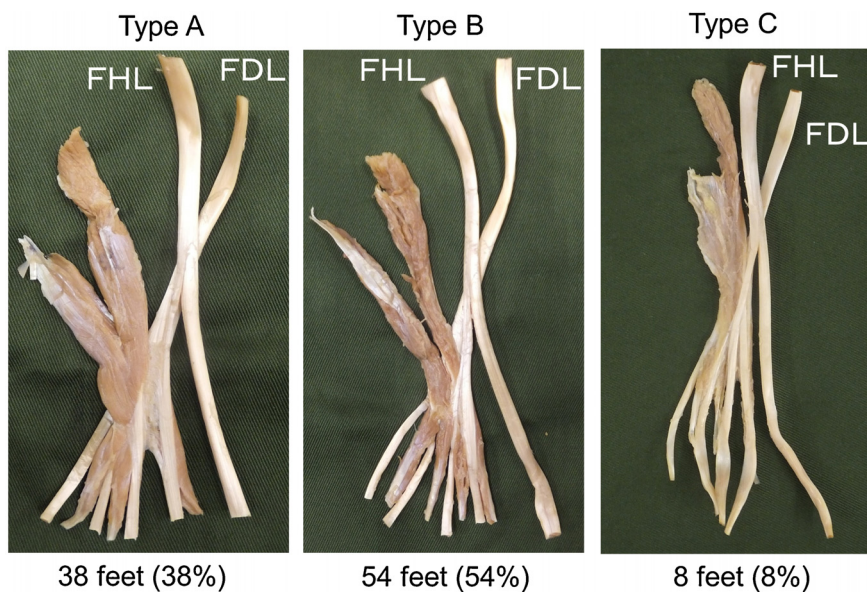
| Type   | Toe 1 (%) | Toe 2 (%) | Toe 3 (%) | Toe 4 (%) |
|--------|-----------|-----------|-----------|-----------|
| Type 1 | 73 ± 12   | 27 ± 12   |           |           |
| Type 2 | 63 ± 10   | 23 ± 6    | 14 ± 7    |           |
| Type 3 | 51 ± 9    | 25 ± 8    | 18 ± 9    | 5 ± 3     |

FHL, flexor hallucis longus.





**Fig. 5.** Classification of interconnections between FHL and FDL tendons. Right foot, posterior view. Type I, single slip from flexor hallucis longus (FHL) to flexor digitorum longus (FDL) tendon; Type II, crossed connection; Type III, single slip from FDL to FHL tendon; Type IV, no connection between tendons; Type V (new to this study), double slip from FHL to FDL tendon.



**Fig. 6.** Classification of connections of FHL tendon slip to lesser toes. Type A, connection from flexor hallucis longus (FHL) to toe 2; Type B, connection from FHL to toes 2 and 3; Type C, connection from FHL to toes 2–4; Type D, connection to all lesser toes. FDL, flexor digitorum longus muscle.

**Table 3**  
Proportion of FHLs with respect to flexor tendon for each toe.

| Type   | Toe 2 (%) | Toe 3 (%) | Toe 4 (%) |
|--------|-----------|-----------|-----------|
| Type 1 | 61 ± 29   |           |           |
| Type 2 | 64 ± 23   | 44 ± 25   |           |
| Type 3 | 72 ± 23   | 69 ± 48   | 22 ± 16   |

FHL, flexor hallucis longus.

#### 4. Discussion

FHL and FDL connections and branches were examined in 100 legs, a larger number than any previous studies involving the FHL.

A quantitative investigation was also conducted into the degree to which the FHL is involved in toe flexion. To the best of our knowledge, no other reports have examined the degree of FHL involvement in toe flexion.

Our results found 38 cases (38%) of Type A, 54 cases of Type B (54%), and eight cases of Type C (8%), branching of the FHL to the lesser toes, with Type B being the most frequent. Type B was also the most frequent in previous studies, at 47% (Wapner et al., 1994), 55% (Plaass et al., 2013), 60.9% (Mao et al., 2014) and 64% (Hur et al., 2011); as such, the previous results support our findings.

From a functional perspective, in the final stages of forefoot contact, about 40% of the body weight is imposed on the toes, and mostly the big toe (Stokes et al., 1979). The tendinous slips

**Table 4**  
Overview of the literature regarding variability of connections from FHL to FDL tendon.

| Study             | Number of feet | Race      | Type I (%) | Type II (%) | Type III (%) | Type IV (%) | Type V (%) |
|-------------------|----------------|-----------|------------|-------------|--------------|-------------|------------|
| O'Sullivan et al. | 16             | n.m.      | 68         | 13          | 19           | 0           | n.m.       |
| LaRue et al.      | 24             | Caucasian | 42         | 0           | 41           | 17          | n.m.       |
| Mulier et al.     | 24             | n.m.      | 58         | 0           | 29           | 13          | n.m.       |
| Plaass et al.     | 60             | Caucasian | 67         | 3           | 30           | 0           | n.m.       |
| Mao et al.        | 64             | Asian     | 96.9       | 3.1         | 0            | 0           | n.m.       |
| Wapner et al.     | 85             | n.m.      | 67         | 0           | 31           | 2           | n.m.       |
| This study        | 100            | Asian     | 86         | 3           | 0            | 0           | 11         |

n.m. = not mentioned. FHL, flexor hallucis longus; FDL, flexor digitorum longus muscle.

**Table 5**  
Review of previous studies concerning variability of connections of FHL tendon slips to lesser toes.

| Study         | Number of feet | Race      | Toe 2 (%) | Toes 2 and 3 (%) | Toes 2–4 (%) | Toes 2–5 (%) |
|---------------|----------------|-----------|-----------|------------------|--------------|--------------|
| Hur et al.    | 50             | Korean    | 8         | 64               | 28           | 0            |
| Plaass et al. | 60             | Caucasian | 33        | 55               | 7            | 0            |
| Mao et al.    | 64             | Asian     | 31.3      | 60.9             | 7.8          | 0            |
| Wapner et al. | 85             | n.m.      | 41        | 47               | 9            | 2            |
| This study    | 100            | Asian     | 37        | 54               | 9            | 0            |

n.m. = not mentioned. FHL, flexor hallucis longus.

of the FHL can provide a more stable base and stronger propulsion for toe-off when walking (Hur et al., 2011). The possibility that differences in the classification of connections of FHL tendon slips to lesser toes may affect walking ability has therefore been suggested.

No cases of Type D or IV were identified in the present study. In previous studies, Type D was reported at 0% (Hur et al., 2011; Mao et al., 2014; Wapner et al., 1994), the same as the result of our study. For Type IV, however, previous studies indicated 0% (Hur et al., 2011; Mao et al., 2014; O'Sullivan et al., 2005; Plaass et al., 2013), 2% (Wapner et al., 1994) and 13–17% (LaRue and Anctil, 2006; Mulier et al., 2007), so a difference was seen between those findings and our study results. In addition, Type V (double slip from FHL to FDL tendon) was seen in 11 legs (11%), representing a new type not recorded in previous classifications (O'Sullivan et al., 2005; Plaass et al., 2013). In terms of overall proportions, our results resembled those of another study of an Asian population (Mao et al., 2014), suggesting that ethnic differences might exist (Tables 4 and 5). The existence of racial differences has been suggested in several papers (Plaass et al., 2013; Mao et al., 2014), but details have not been described.

Regarding the various flexor tendons, the proportion of FHL branching to toes 2 and 3 was high, at approximately 50–70%. Consequently, considering the branching type and CSA proportion, the FHL was conjectured to not only act to flex the hallux, but also play a significant role in the flexion of toes 2 and 3. The tendinous slips of the FHL can provide a more stable base and stronger propulsion for toe-off (Hur et al., 2011). Anatomically speaking, the tendinous slips of the FHL are surmised to be agonists in the flexion of toe 2 (Mao et al., 2014). Our results thus support these previous studies, and provide important information for future clarification of the functional role of FHL tendinous slips.

Tendon transfer of the FHL and FDL is widely used as a treatment for Achilles tendinitis, rupture of the Achilles tendon, and dysfunction of the tibialis posterior muscle (DiPaola and Raikin, 2007; Wegrzyn et al., 2010; Schon et al., 2013), and good postoperative results have been reported. Most studies found no obvious asymmetry in walking and no subjective loss of push-off (Coull et al., 2003; Martin et al., 2005). However, Hahn et al. found a loss of active plantar flexion of the big toe during walking, and pressures and forces under the big toe were reduced. Multiple studies (Wapner et al., 1994; Monroe et al., 2000; Coull et al., 2003; Richardson et al., 2009) have demonstrated few patients reporting

problems with a decrease in active range of motion and power of the first metatarsophalangeal joint. Our results therefore show that if tendon transfer is chosen for surgical treatment of Achilles tendon rupture and dysfunction of the tibialis posterior muscle, transection of the FDL would probably still provide sufficient function to the lesser toes. Furthermore, 100% of feet showed a connection from FHL to FDL, and this connection might contribute to residual function of the lesser toes after transfer. These results may provide important information in terms of facilitating rehabilitation after tendon transfer for Achilles tendon rupture and dysfunction of the tibialis posterior muscle.

The information gained in the research described here, concerning the function of the FHL in flexion of the lesser toes, may be quite important. However, our study contained a number of limitations, the first being that the study focused on CSAs of tendons, and the actual actions of the FHL on lesser toe flexion were not investigated. A second limitation was that rigid cadavers were used, and CSAs from our study may thus differ from those of tendons in living subjects.

## 5. Conclusions

Based on our findings, the actions of the FHL are surmised to be strongly involved not only in flexion of the hallux, but also in flexion of toes 2 and 3. These results may provide important information in terms of future clarification of the functional roles of tendinous slips from the FHL, and may help in rehabilitation after tendon transfer for Achilles tendon rupture and dysfunction of the tibialis posterior muscle.

## Acknowledgments

The authors would like to acknowledge and thank those anonymous individuals who generously donated their bodies so that this study could be performed. This study was supported by a Grant-in-Aid from our university (H26B04).

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.aanat.2015.11.008>.

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