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BRIEF COMMUNICATION

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Associations of muscle volume of individual human plantar intrinsic foot muscles with morphological profiles of the foot

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Abstract

Human plantar intrinsic foot muscles consist of 10 muscles that originate and insert within the sole of the foot. It is known that the anatomical cross-sectional area (ACSA) and muscle thickness of two plantar intrinsic foot muscles, the flexor hallucis brevis (FHB) and abductor hallucis (ABH), associate with morphological parameters of the foot, such as total and truncated foot length and navicular height. However, it is unclear how the size for each of the plantar intrinsic foot muscles associates with various morphological profiles of the foot. This study aimed to elucidate this subject. By using magnetic resonance imaging (MRI), serial images of the right foot were obtained in 13 young adult men without foot deformities. From the obtained MR images, ACSA for each of the individual plantar intrinsic foot muscles was analyzed along the foot length, and then its muscle volume (MV) was calculated. The analyzed muscles were the abductor digiti minimi (ABDM), ABH, adductor hallucis oblique head (ADDH-OH), adductor hallucis transverse head (ADDH-TH), flexor digitorum brevis (FDB), FHB, and quadratus plantae (QP). Furthermore, MV of the whole plantar intrinsic foot muscle (WHOLE) was defined as the total MVs of all the analyzed muscles. As morphological parameters, total foot length, truncated foot length, forefoot width, ball circumference, instep circumference, navicular height, great toe eversion angle, and little toe inversion angle were measured using a laser three-dimensional foot scanner in standing and sitting conditions. In addition, navicular drop (ND) and normalized truncated navicular height (NTNH) were also calculated as medial longitudinal arch (MLA) height indices. The MV of WHOLE was significantly associated with the forefoot width, ball circumference, and instep circumference ($r = 0.647–0.711$, $p = 0.006–0.013$). Positive correlations were found between the forefoot width and MV of FHB, FDB, and QP ($r = 0.564–0.653$, $p = 0.015–0.045$), between the ball circumference and MV of QP ($r = 0.559$, $p = 0.047$), between the instep circumference and MV of FHB ($r = 0.609$, $p = 0.027$), and between the little toe inversion angle and MV of QP ($r = 0.570$, $p = 0.042$). The MVs of ABH, ABDM, and ADDH-OH were not significantly correlated with any morphological parameters of the foot. Similarly, no significant correlations were found between MV of each muscle and either of the MLA height indices (ND and NTNH). Thus, the current results indicate that forefoot width and circumferential parameters (instep and ball circumference), not MLA height, associate with the size of the whole plantar intrinsic foot muscles, especially those specialized in toe flexion (FHB, FDB, and QP).

KEYWORDS
bipedalism, foot arch, foot dimension, muscle morphology, muscle volume

1 | INTRODUCTION

The anatomical structures of human feet (e.g., the enlarged calcaneus, adducted and non-opposable great toe, shortened lesser toes, and well-developed longitudinal arch) are recognized as influential hallmarks to enable habitual bipedalism (Bramble & Lieberman, 2004). Evolutionally, the transition from the arboreal to terrestrial locomotion caused changes in the functional requirements of the human foot (e.g., loss of the grasping function of the great toe; Moriyama, 1981), resulting in morphological adaptations of human plantar intrinsic foot muscles (Arakawa et al., 2003). Therefore, examining how the size of plantar intrinsic foot muscles associates with morphological profiles of the foot may provide useful information for understanding the changes in functional roles of these muscles with adaptation to habitual bipedalism.

In general, the human foot structure is characterized by the multidimensional morphological parameters, such as foot length, width, circumference, and navicular height (Kouchi, 1998; Waseda et al., 2014). Electromyographic studies have reported that the medial longitudinal arch (MLA) height decreases with impaired activation of plantar intrinsic foot muscles caused by the tibial nerve block (Fiolkowski et al., 2003). Moreover, increased activation of these muscles by electrical stimulation counters the collapse of MLA (Kelly et al., 2014). These findings suggest that the morphological development of plantar intrinsic foot muscles associates with that of the foot, especially the magnitude of the MLA height. In fact, some studies (Angin et al., 2014; Latey et al., 2018; Taş et al., 2018) have provided evidence supporting this. For example, positive correlations were found between the anatomical cross-sectional area (ACSA) of the abductor hallucis (ABH) and dorsal arch height (the foot height at 50% of foot length) in sitting/standing conditions and between ACSA of the flexor hallucis brevis (FHB) and the six-item foot posture index (FPI-6) score (Latey et al., 2018). In addition, individuals with the flat foot (pes planus or pronated foot), characterized by lowered MLA, have small ACSAs and muscle thickness of ABH and FHB compared with those with the normal foot (Angin et al., 2014). On the other hand, another study reported that individuals with the flat foot have larger muscle thickness of the ABH compared with those with the normal foot (Taş et al., 2018). Furthermore, it is known that total and truncated foot length positively associates with the ACSAs of ABH and FHB (Latey et al., 2018). However, the prior studies cited here have only examined the interrelationship between the limited morphological profiles of the foot and the size for three (ABH, FDB, and FHB) of the 10 human plantar intrinsic foot muscles (Kura et al., 1997).

This study aimed to elucidate how the size for each of the individual plantar intrinsic foot muscles associates with the morphological profiles of the foot. To this end, we determined the muscle volume (MV) for each of the plantar intrinsic foot muscles as a representative parameter of muscle size. Then, we tested a hypothesis that MV for each muscle would be associated with not only the MLA height but also other parameters such as foot length and width.

2 | METHODS

2.1 | Participants

Thirteen male university students (age, 22.4 ± 3.0 years; height, 170.5 ± 5.0 cm; body mass, 63.7 ± 5.7 kg; mean ± standard deviation) who had no history of a diagnosed neuromuscular disorder or a lower limb injury voluntarily participated in this study by convenience sampling. They usually wore sports shoes outside but not inside the house. This study was approved by the Ethics Committee of Ritsumeikan University (BKC-2018-084).

2.2 | Determination of MV

The participants were positioned on the table of a 3.0 T magnetic resonance (MR) system (Magnetom Skyra, Siemens Healthcare) and their right foot and ankle were incased in the ankle coil (Foot/Ankle coil, Siemens Healthcare). The ankle joint was maintained at 90° of plantarflexion with Velcro straps to reduce motion artefacts. Serial T1-weighted MR images of the whole foot were scanned with the same parameters conducted by our previous study (Kusagawa et al., 2022). The obtained MR images were analyzed by using image analysis software (SliceOmatic version 5.0Rev-3b, Tomovision). One examinator (Y.K.) manually traced and segmented the ACSA of each of seven plantar intrinsic foot muscles (detailed below) in every MR image from the most proximal to distal MR images in which the muscles were visible (Figure 1B) by using a graphics tablet (Intuos pro, Wacom Co., Ltd.). The measured muscles were abductor digiti minimi (ABDM), ABH, adductor hallucis oblique head (ADDH-OH), adductor hallucis transverse head (ADDH-TH), FDB, FHB, and quadratus plantae (QP). The other three muscles (i.e., lumbricals, flexor digiti minimi, and plantar interossei) were excluded from the analysis due to their small size and resulting difficulties in visually separating these muscles. The MV of individual muscles was calculated

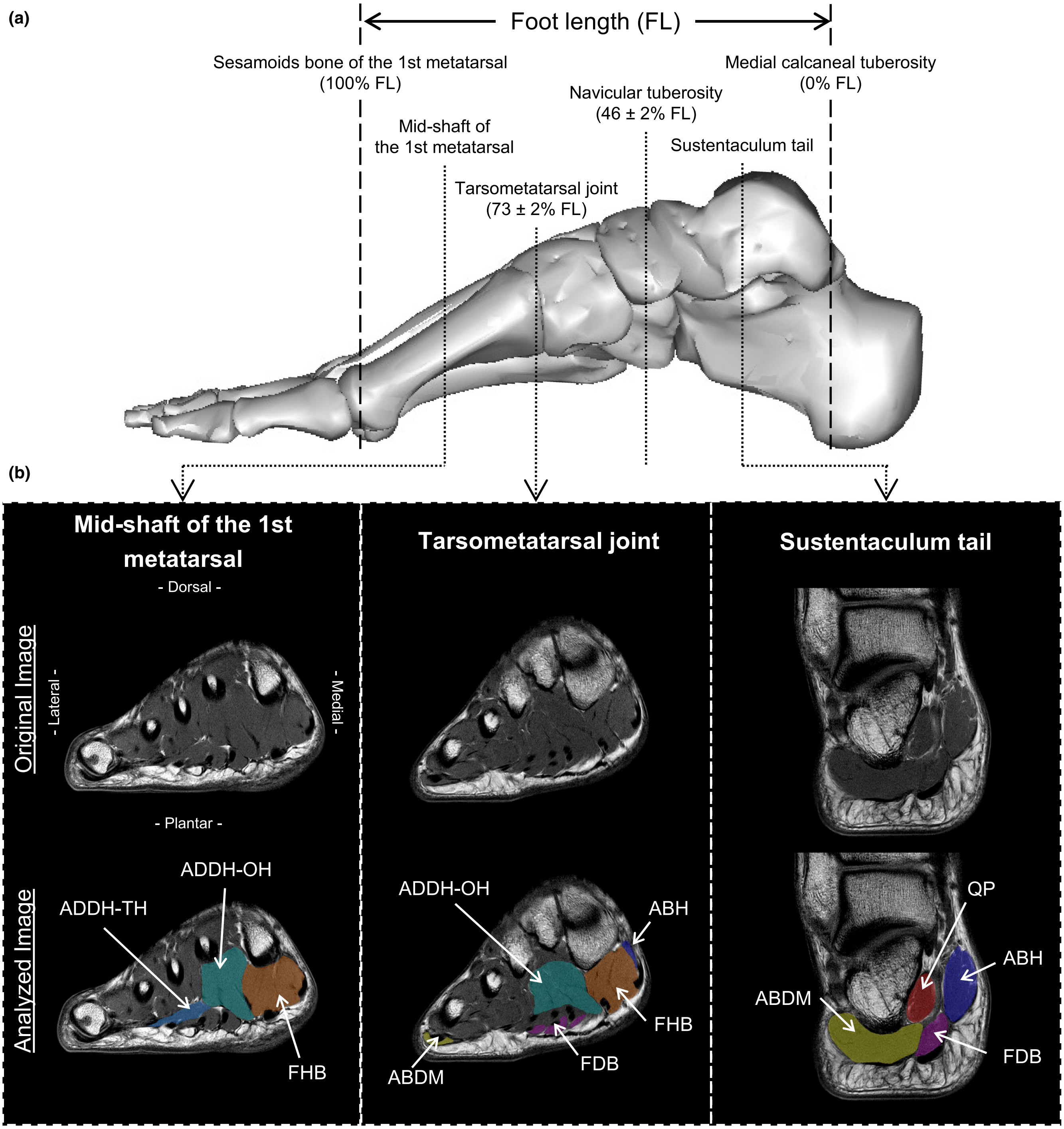

FIGURE 1 Definitions of foot length (a) and T1-weighted MR images (b) of the right foot. ABDM, abductor digiti minimi; ABH, abductor hallucis; ADDH-OH, adductor hallucis oblique head; ADDH-TH, adductor hallucis transverse head; FDB, flexor digitorum brevis; FHB, flexor hallucis brevis; QP, quadratus plantae. The foot images in the A was created using “BodyParts3D, © The Database Center for Life Science licensed under CC Attribution-Share Alike 2.1 Japan.”

by summing all ACSAs for the analyzed muscle multiplied by the slice thickness. Similarly, the total MV for all the analyzed muscles was calculated and referred to as the MV of the WHOLE. Intra-rater repeatability for measuring MV was confirmed as good to excellent for each muscle (Kusagawa et al., 2022). Furthermore, FL was calculated from the number of slices between the medial calcaneal tuberosity and the sesamoids bone of the first metatarsal (Figure 1a), multiplied by the slice thickness. The position of each image was expressed as the value relative to FL (0% FL: the medial calcaneal tuberosity, 100% FL: the sesamoids bone of the first metatarsal; Figure 1a). The ACSA of each muscle was calculated at 5% intervals of FL by linear interpolation using Excel

(Microsoft Corp.; Kusagawa et al., 2022). The ACSA distributions at 5% intervals of FL of each analyzed muscle and WHOLE are shown in Figure 2.

2.3 | Measurements of the morphological parameters of the foot

The participants bilaterally stood with bare feet and a sticker was put on the most prominent point of the navicular tuberosity. Then, their right foot was incased in a laser three-dimensional foot scanner (JMS-3110, Dream GP Inc.) and the following parameters were measured: total and truncated foot length, forefoot width, great toe eversion and little toe inversion angle, ball and instep circumference, and navicular height. Additionally, navicular height was measured in a sitting position using the same scanner. Furthermore, the navicular drop (ND), defined as the difference in navicular height between the sitting and standing conditions, and normalized truncated navicular height (NTNH), defined as the ratio of navicular height in the standing to truncated foot length (Menz & Munteanu, 2005; Murley et al., 2009), were obtained as the indices of MLA height. The navicular height and its normalized value (i.e., NTNH) have been shown to be moderately to highly correlated with radiographic measures (calcaneal inclination and calcaneal-first metatarsal angle; Menz & Munteanu, 2005, Murley et al., 2009), which is recognized as a gold standard technique for assessing the MLA height.

2.4 | Statistical analysis

Normality of measured variables was assessed by Shapiro–Wilk test, and was confirmed in all variables except for great toe eversion angle. Thus, to examine the associations between MV of plantar intrinsic foot muscles and the morphological parameters, Spearman's rank-order correlations were calculated when concerning great toe eversion angle, and otherwise Pearson's correlation coefficients were calculated. The level of significance was set at $p < 0.05$. All data were analyzed using SPSS version 27.0 (IBM Co.).

3 | RESULTS

The largest MV value was observed in ABH, followed by FDB, ABDM, FHB, ADDH-OH, QP, and ADDH-TH (Figure 2). Table 1 presents the associations between MV of the plantar intrinsic foot muscles and morphological parameters of the foot. The MV of WHOLE was significantly associated with the forefoot width, ball circumference, and instep circumference. Positive correlations were found between the forefoot width and the MV of FDB, FHB, and QP, between ball circumference and the MV of QP, between instep circumference and the MV of FHB, and between little toe inversion angle and MV of QP. However, a negative correlation was found between truncated foot length and MV of ADDH-TH. The MV of ABDM, ABH, and ADDH-OH were not significantly correlated with any anthropometric parameters of the foot. Similarly, no correlations were found between MV of each muscle and any of the MLA height indices.

4 | DISCUSSION

The major findings obtained here were that (1) the indices of MLA height were not significantly correlated with the MV of any muscles, and (2) the forefoot width and circumferential parameters (instep and ball circumference) were positively correlated with the MV of WHOLE, especially the muscles specialized in toe flexion (FDB, FHB, and QP). These results partially supported our hypothesis and indicate that the size of the limited plantar intrinsic muscles associates with foot morphological parameters other than the indices of MLA height.

The indices of MLA height were not significantly correlated with MV of any muscles (Table 1). This denied our hypothesis derived from the previous reports indicating the association of the size of ABH and FHB with morphological profiles of the foot (Angin et al., 2014; Latey et al., 2018; Taş et al., 2018). This unexpected result might be due to the following possibilities. First, the indices representing the MLA height differed between the present and previous studies. The present study is the first to determine the relationship between the size of individual plantar intrinsic foot muscles and MLA height using indices directly and quantitatively assessing navicular height. On the other hand, the previous studies visually assessed and scored (5-point scale) the MLA height in the procedure of the FPI-6 scoring (Angin et al., 2014, Latey et al., 2018, Taş et al., 2018), which may not precisely reflect the magnitude of the MLA height. Second, this study measured MV as a representative variable of muscle size. The prior studies (Angin et al., 2014, Latey et al., 2018, Taş et al., 2018) quantified muscle size as ACSA and muscle thickness. However, these variables depend on the site where these are determined (Blazevich et al., 2006; Fukunaga et al., 1992) and therefore only provide regional/limited information about the entire muscle size (i.e., less robust indices than MV). Finally, the role of the plantar intrinsic foot muscles is considered as posture dependent (Kurihara et al., 2020). The activation of plantar intrinsic foot muscles increases by applying an incremental vertical load against a lower limb in the seated position (Kelly et al., 2014), while the activation level of these muscles did not reach the same level in the bilateral stance even though the identical load was applied on the foot (Kurihara et al., 2020). These three aspects would explain why the size of the plantar intrinsic foot muscles did not associate with MLA height, which was directly assessed in this study.

The observed positive correlations of the forefoot width and circumferential parameters with MV of WHOLE and several individual plantar intrinsic foot muscles partly supported our hypothesis. Habitually barefoot populations have wider forefoot than those with a conventional shoe (Ashizawa et al., 1997). In addition, it is known that wearing minimalist shoes, enabling to imitate barefoot running

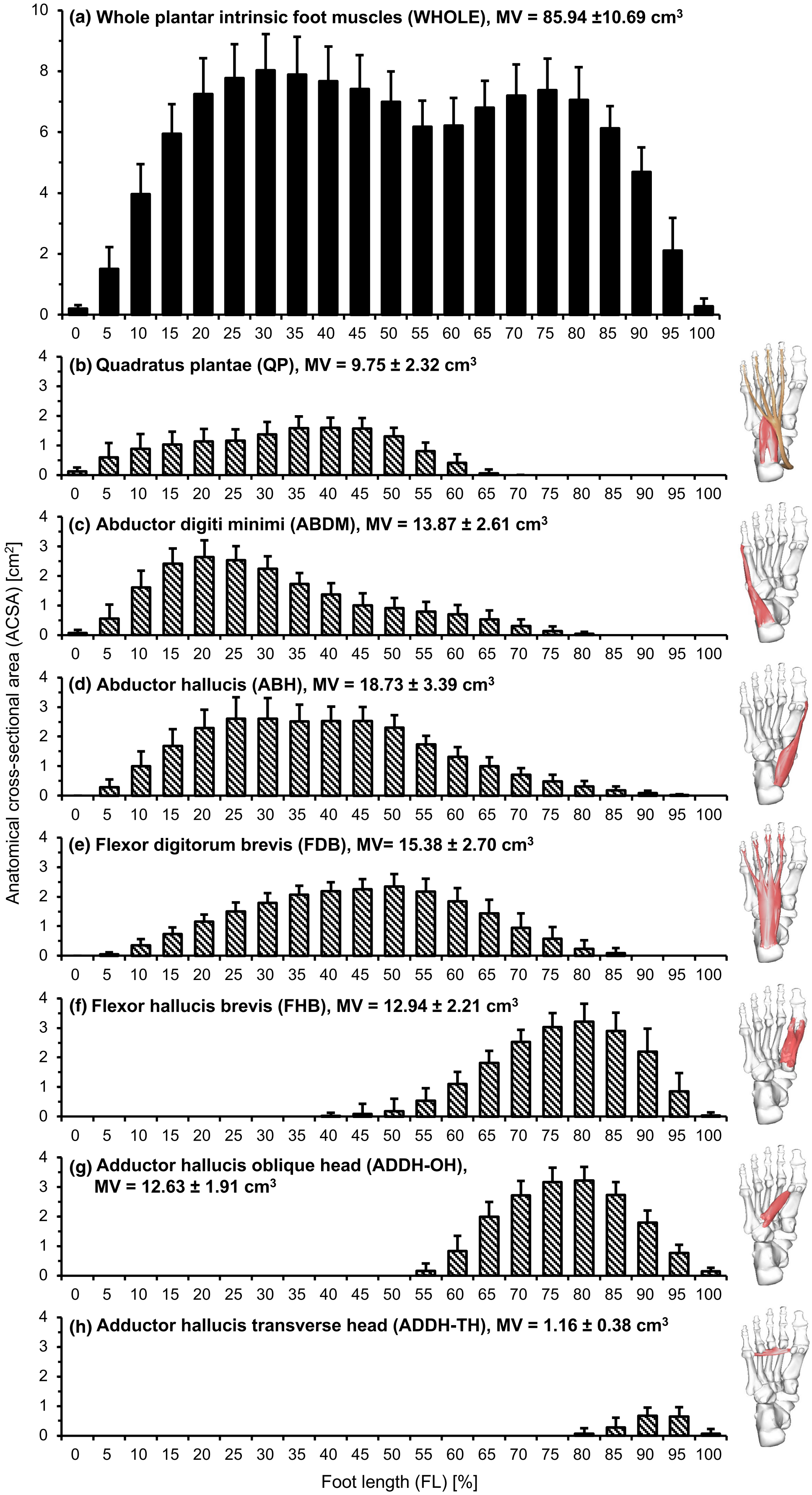
(a) Whole plantar intrinsic foot muscles (WHOLE), MV = 85.94 ±10.69 cm³
(b) Quadratus plantae (QP), MV = 9.75 ± 2.32 cm³
(c) Abductor digiti minimi (ABDM), MV = 13.87 ± 2.61 cm³
(d) Abductor hallucis (ABH), MV = 18.73 ± 3.39 cm³
(e) Flexor digitorum brevis (FDB), MV= 15.38 ± 2.70 cm³
(f) Flexor hallucis brevis (FHB), MV = 12.94 ± 2.21 cm³
(g) Adductor hallucis oblique head (ADDH-OH),
MV = 12.63 ± 1.91 cm³
(h) Adductor hallucis transverse head (ADDH-TH), MV = 1.16 ± 0.38 cm³
Anatomical cross-sectional area (ACSA) [cm²]
Foot length (FL) [%]
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

TABLE 1 Correlation coefficients between the MV of plantar intrinsic foot muscles and anthropometric parameters of foot

	QP *r*	ABH *r*	FDB *r*	ABDM *r*	FHB *r*	ADDH-OH *r*	ADDH-TH *r*	WHOLE *r*
Length								
Total foot length	0.369	0.242	0.416	0.015	0.134	0.318	−0.534	0.331
Truncated foot length	0.321	0.222	0.390	−0.027	0.144	0.288	−0.560*	0.293
Width								
Forefoot width	0.564*	0.390	0.653*	0.448	0.598*	0.482	−0.542	0.711**
Circumference								
Ball circumference	0.559*	0.440	0.516	0.518	0.531	0.293	−0.404	0.665*
Instep circumference	0.348	0.405	0.483	0.540	0.609*	0.449	−0.467	0.647*
Toe angle								
Great toe eversion angle	−0.385	0.115	0.104	−0.044	0.236	−0.500	−0.104	−0.093
Little toe inversion angle	0.570*	−0.002	0.241	−0.146	−0.145	0.269	0.376	0.180
MLA height								
Navicular height at standing position	0.078	−0.015	0.343	0.354	0.166	0.226	−0.197	0.253
Navicular height at sitting position	0.131	−0.011	0.262	0.366	0.096	0.260	−0.174	0.241
ND	0.181	0.016	−0.305	0.020	−0.256	0.104	0.096	−0.059
NTNH	−0.030	−0.091	0.162	0.319	0.089	0.120	0.041	0.124
Ratio								
Foot width/total foot length	−0.056	−0.017	−0.062	0.313	0.270	−0.052	0.297	0.100
Foot width/truncated foot length	−0.010	−0.007	−0.044	0.350	0.230	−0.021	0.355	0.126
Truncated foot length/total foot length	−0.147	−0.039	−0.039	−0.215	0.069	−0.085	−0.267	−0.117

Note: Ball circumference indicates the total perimeter between the most medial point the first metatarsophalangeal joint and the most lateral point of the fifth metatarsophalangeal joint. Instep circumference indicates that the total perimeter of the longitudinal section of 55% of total foot length.
Abbreviations: ABDM, Abductor digiti minimi; ABH, Abductor hallucis; ADDH-OH, Adductor hallucis oblique head; ADDH-TH, Adductor hallucis transverse head; FDB, Flexor digitorum brevis; FHB, Flexor hallucis brevis; MLA; Medial longitudinal arch; ND, Navicular drop; NTNH, Normalized truncated navicular height; QP, Quadratus plantae; WHOLE, whole plantar intrinsic foot muscles.
Significance of correlations coefficients is indicated as follows: *$p < 0.05$, **$p < 0.01$.

or walking (Squadrone & Gallozzi, 2009), increases plantar pressure in the forefoot region (Bergstra et al., 2015) and induces hypertrophy of plantar intrinsic foot muscles to counter the load against the foot (Ridge et al., 2019). Thus, the observed correlations between forefoot width and circumferential parameters and the MV of plantar intrinsic foot muscles, especially those that run along the longitudinal direction of the foot and specialized in toe flexion (FHB, FDB, QP), may reflect the structural development of human feet to adapt to the loads produced by locomotion.

Interestingly, truncated foot length (i.e., longitudinal distance of the foot) was found to be negatively correlated with the MV of ADDH-TH which runs along the transverse direction of the foot. This somewhat contradicts with the prior finding that the total and truncated foot length were positively associated with the size of ABH and FHB (Latey et al., 2018). The reason for this contradiction is unknown but might involve the change of functional requirement in the ADDH-TH via the transmission from arboreal to terrestrial lifestyle. In non-hominoid primates, the great toe, similarly to the thumb, requires the opposable movement to grasp and balance on the branches (Moriyama, 1981). Consequently, non-hominoid primates' MV of ADDH-TH, which acts on the opposable movement of the great toe, is about 0.9–2.0 times larger than that of

FIGURE 2 Distribution of muscle anatomical cross-sectional is along the % foot length (0%: calcaneal medial tuberosity, 100%: sesamoid bones of first metatarsal). The bar of each graph represents the mean (+SD) of anatomical cross-sectional area for all participants ($n = 13$). (a) Whole plantar intrinsic foot muscles (WHOLE) indicate all analyzed plantar intrinsic foot muscles; (b) quadratus plantae (QP); (c) abductor digiti minimi (ABDM); (d) abductor hallucis (ABH); (e) flexor digitorum brevis (FDB); (f) flexor hallucis brevis (FHB); (g) adductor hallucis oblique head (ADDH-OH); (h) adductor hallucis transverse head (ADDH-TH). MV: Muscle volume. The muscle images on the right side of each graph were created using "BodyParts3D, © The Database Center for Life Science licensed under CC Attribution-Share Alike 2.1 Japan."

ADDH-OH (Oishi et al., 2018). In human feet which no longer require the opposable movement of the great toe (Moriyama, 1981), however, the MV of ADDH-TH was the smallest among the plantar intrinsic foot muscles and one-tenth as large as that of ADDH-OH (Figure 2). On the other hand, the longer foot length is known to be an anatomical factor for the effective bipedal locomotion (Adamczyk & Kuo, 2013). Taking these aspects, it seems that as a result of habitual bipedalism in humans, less functional requirements of ADDH-TH might have induced the smallest MV and consequently yielded a negative association with the truncated foot length. Further investigation would be needed to interpret this interesting association.

4.1 | Limitations

This study recruited only young males. The reason for this was to avoid potential confounding influences of sex differences in the MLA height (Zhao et al., 2020) and of age-related reduction in the size of plantar intrinsic foot muscles (Mickle et al., 2016). We have no information on the influences of age and sex on the relationship between the size of plantar intrinsic foot muscle and indices of the MLA height. In relation to this, most of the participants in the present study can be classified as having normal feet based on their NTNH value (Murley et al., 2009). Thus, it is unclear whether the current findings can be applied to other populations, such as females, older adults, and those with foot deformities. Finally, although the participants usually wore sports shoes outside but not inside the house, we did not record the details of the shoes they wore (e.g., stiffness of the shoe sole cushioning or the shape of the toe). Further study is warranted to clarify whether current findings can be generalized.

5 | CONCLUSION

In conclusion, the overall results of the present study suggest that forefoot width and circumferential parameters, not medial longitudinal arch height, associates with the MV of the whole plantar intrinsic foot muscles, especially those specialized in toe flexion.

AUTHOR CONTRIBUTIONS

YK, TK, and IT conceptualized and designed this study; YK and TK performed experiments and acquired/analyzed the data; YK and TK and YK, TK, SM, TS, and HK interpreted the data; YK and HK drafted the manuscript; all authors approved the final manuscript.

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DATA AVAILABILITY STATEMENT

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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