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Strength and size relationships of toe flexor muscles in three different functional force production tasks

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Purpose: Toe flexor strength (TFS) has been determined to evaluate the toe flexor muscle function. However, it is unclear how strength and size relationships of toe flexor muscles vary depending on the toes intended for force production. We aimed to clarify this by examining the relationship between TFS and toe flexor muscle size, and hypothesized TFS produced by all toes (TFS-All), the great toe (TFS-Great) and lesser toes (TFS-Lesser) would be specifically associated with the size of the muscles specialized in each corresponding toe flexion. *Methods*: The maximal anatomical cross-sectional area ($ACSA_{max}$) of each toe flexor muscle was measured by magnetic resonance imaging in twenty healthy young men. The three types of TFS were measured using a custom-made toe push dynamometer. *Results*: TFS-All was significantly associated with $ACSA_{max}$ of the adductor hallucis transverse head (ADDH-TH) ($r = 0.58$, $P = 0.01$) and flexor hallucis brevis (FHB) ($r = 0.56$, $P = 0.01$). TFS-Great and TFS-Lesser were not significantly correlated with $ACSA_{max}$ of any analyzed muscles, except for a significant correlation between TFS-Lesser and dorsal/plantar interosseous muscle ($r = 0.48$, $P = 0.03$). *Conclusions*: The size of two plantar intrinsic foot muscles, FHB, anatomically specialized for the great toe flexion, and ADDH-TH, supplementary flex the great toe, may be the determinant for TFS-All. However, TFS-Great and TFS-Lesser are not associated with the size of the muscles anatomically specialized in each corresponding toe flexion, perhaps due to difficulty in maximally and separately activating individual muscles (i.e., neural/anatomical reasons) during the TFS-Great and TFS-Lesser production.

Key words: *toe push strength, plantar intrinsic foot muscles, extrinsic foot muscles, metatarsophalangeal joint*

1. Introduction

The measurement of the maximum toe flexor strength (TFS) is used to determine the force generation capacity of the toe flexor muscles, comprising the plantar intrinsic foot muscles and extrinsic toe flexors [9]. TFS is positively associated with postural control [6] and athletic performance such as sprinting [38], jumping [16], [38], [42], and change of direction [43]. On the other hand, a low level of TFS is related to a high risk of falls [22], [24]. Furthermore, an impaired activity of the toe flexor muscles (especially the plantar intrinsic foot muscles) via a tibial nerve block causes decreases in positive work production at the foot and ankle in walking, running [7] or jumping [35], and negative work production at these segments in landing [35]. Thus, toe flexor muscles and their force generation capacity, i.e., TFS, play an important role in realizing daily life and sport activities.

Among the constituents of toe flexor muscles, some flex the great toe (e.g., flexor hallucis brevis (FHB) and flexor hallucis longus [FHL]), while others cause lesser toes flexion (e.g., flexor digitorum brevis (FDB) and flexor digitorum longus (FDL)) [27]. Moreover, some of the plantar intrinsic foot muscles cause toes

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flexion only, while others mainly produce the adduction/abduction and assist in the flexion of toes [27]. In addition, the somatotopic representation of all five toes in human is divided into the great toe alone and four lesser toes [11]. Given the functional profiles of the individual toe flexor muscles and unique sensorimotor system in humans, the magnitude of TFS may be affected by the functional unit (i.e., great toe or lesser toes) selected for force production.

TFS has been mainly determined using toe push [9], [16], [31]–[34], [43], toe grip [1], [16], [17], [25], [26], [29], [32], [39]–[41], and hand-held [21], [37] dynamometers. Most of the previous studies that used these dynamometers have adopted three different manners of the toes intended for the force production: all toes (TFS-All), the great toe only (TFS-Great), and the lesser toes (TFS-Lesser). It is known that the magnitude of TFS production depends on the toe(s) intended for force production regardless of the type of device utilized [1], [23], [29], [37]. Namely, TFS-Great can produce approximately 1.5 times greater force than TFS-Lesser [23], and TFS-Lesser – force approximately by one-third greater than TFS-All [1]. Considering these findings together with the functional differences in individual toe flexor muscles, it is likely that the muscles which specifically contribute to the TFS production may differ in relation with the conditions of the toes intended for force production. This idea will be clarified by examining how TFS, determined in each of the corresponding conditions, is associated with the size of individual toe flexor muscles, because the force generation capacity of a muscle is basically related to its size [8], [13].

Many studies have already examined how TFS is associated with the size of the toe flexor muscles [1], [17], [18], [21], [23]. In most of the previous studies, muscle size has been determined as the anatomical cross-sectional area (ACSA) and/or muscle thickness of a limited number of individual plantar intrinsic foot muscles [1], [21], [23] or ACSA of several muscles as one mass [17]. Theoretically, the physiological cross-sectional area (PCSA) of a muscle is the strongest determinant for its maximum force production capacity [12]. On the other hand, the correlation coefficients of muscle volume (MV) and maximum ACSA ($ACSA_{max}$) with muscle strength (i.e., knee extension and elbow flexion/extension strength) in humans have been found to be comparable to those of PCSA [2], [8]. A previous study has examined the associations of either MV or $ACSA_{max}$ of individual toe flexor muscles with TFS-All [18]. They found that the adductor hallucis oblique head (ADDH-OH) was consistently selected as a major contributor to TFS-All measured using a toe grip dynamometer when either MV or $ACSA_{max}$ was used as a muscle size measure [18]. However, it is unknown how the strength and size relationships of the toe flexor muscles vary depending on the toes intended for force production. Clarifying this will provide useful information to deepen our knowledge concerning the method to evaluate the functions of toe flexor muscles individually and training strategies aiming to enhance the force generation capacity of toe flexor muscles.

This study aimed to investigate whether the relationship between the toe flexor muscle size and TFS differs depending on the toe(s) intended for force production. To this end, we firstly determined the size (MV and $ACSA_{max}$) of each toe flexor muscle using magnetic resonance imaging (MRI). The TFS-All, TFS-Great, and TFS-Lesser were then measured using a custom-made toe push dynamometer [16], [31], [43], and we further examined how the size for each of the toe flexor muscles associates with TFS determined in each of the three conditions of toe(s) intended for force production. We hypothesized that both TFS-All and TFS-Great would be associated with the size of the muscles specialized in great toe flexion (i.e., FHB and FHL), while TFS-Lesser is related to the size of the muscles specialized in lesser toes flexion (i.e., FDB and FDL).

2. Materials and methods

Participants

Twenty male university students (age: 23.1 ± 2.9 yrs; height: 171.2 ± 4.5 cm; body mass: 65.5 ± 6.7 kg; mean ± standard deviation [SD]) who had no toe/foot deformities on visual observation and no history of a diagnosed neuromuscular disorder or lower limb injury voluntarily participated by convenience sampling. They wore athletic shoes outdoors on a daily basis, but not indoors (e.g., inside the house). This study was approved by the university institutional review board, and all participants provided prior written informed consent according to the guidelines of the Declaration of Helsinki.

Experimental procedure

At the beginning of the study, all participants underwent measurements of their physical characteristics (body mass and height). Foot and lower leg images were obtained by MRI. After the completion of the morphological and MRI measurements, three types of TFS were measured using a custom-made toe push dynamometer, as follows: TFS-All (TFS produced by all toes), TFS-Great (TFS produced by the great toe), and TFS-Lesser (TFS produced by lesser toes). All TFS measurements were conducted in a randomized order within a single session of a day.

Determination of muscle size

The participants were placed in the prone position on the examination table of a 3.0 T MR system (Magnetom Skyra, Siemens Healthcare, Erlangen, Germany). Then, the right foot and ankle were encased in the ankle coils (Foot/Ankle coil, Siemens Healthcare), and the ankle joint was positioned at 90° of plantarflexion (neutral position) using a Velcro strap to reduce motion artefacts. In accordance with the previous studies [18], [19], serial longitudinal relaxation time (T1)-weighted MR foot images of the range from the posterior part of the calcaneus to beyond the metatarsophalangeal (MTP) joint were acquired using a fast spin-echo sequence, with the following parameters: repetition time = 700 ms, echo time = 12 ms, average = 3, slice thickness = 3.5 mm, gap between slices = 0 mm, field of view = 125 × 125 mm, flip angle = 120°, and matrix = 512 × 512. To obtain MR images of the right lower leg, the participants were positioned on the examination table with their lower legs placed parallel to the main magnetic field. Serial lower leg images were acquired from the knee cleft just proximal to beyond the medial/lateral malleolus using the following sequential parameters: repetition time = 700 ms, echo time = 9.4 ms, average = 3, slice thickness = 5 mm, gap between slices = 5 mm, field of view = 360 × 360 mm, and flip angle = 120°, matrix = 512 × 512. The data acquisition time for each foot and lower leg scan was approximately 4 and 5 min, respectively.

Every MR image of the foot and lower leg was analyzed by one examiner (YK) using a specially designed image analysis software (SliceOmatic, version 5.0 Rev-3b, Tomovision Inc., Montreal, Canada). Non-contractile tissues, including the bone, tendon, fat, connective tissue, nerve tissue, and blood vessels, were carefully excluded wherever possible. From the foot images, the ACSAs of nine plantar intrinsic foot muscles, including the abductor digiti minimi (ABDM), abductor hallucis (ABDH), adductor hallucis oblique head (ADDH-OH), ADDH transverse head (ADDH-TH), flexor digitorum brevis (FDB), flexor digiti minimi (FDM), flexor hallucis brevis (FHB), dorsal/plantar interosseous muscle (INT), and quadratus plantae (QP), were manually outlined in every image from the most proximal to the distal image in which the muscle was visible. The lumbricals muscle was excluded from the analysis because this muscle could not be visually separated from flexor digitorum longus tendons.

From a series of analyzed MR images, the maximal ACSA value for each individual plantar intrinsic foot muscle was defined as the $ACSA_{max}$. Moreover, the ACSAs of the individual extrinsic toe flexor muscles (i.e., FHL and FDL) were analyzed from the lower leg images, and the maximal ACSA value was defined as the $ACSA_{max}$. In our previous study [18], we assessed the intra-rater repeatability of the analysis of the $ACSA_{max}$ of individual plantar intrinsic foot muscles and extrinsic toe flexors by calculating intraclass correlation coefficients (ICC). The results showed that the ICC (1, 3) values of $ACSA_{max}$ of individual muscles ranged from 0.869 to 0.999 [18], confirming good-to-excellent intra-rater repeatability [15]. Furthermore, the $ACSA_{max}$ of the following four muscle groups was calculated as the sum of the $ACSA_{max}$ of each constituent muscle: all analyzed plantar intrinsic foot muscles, intrinsic great toe (ABDH, ADDH-OH, ADDH-TH, and FHB), lesser toes flexors (ABDM, FDB, FDM, INT, and QP), and extrinsic toe flexors (FHL and FDL). In addition to $ACSA_{max}$, we also assessed MV as a muscle size measure [18], but these two measures of muscle size resulted in the same interpretation and therefore data are only reported as $ACSA_{max}$ to avoid redundancy.

Measurement of TFS

We modified a custom-made toe push dynamometer (T.K.K. 1268, Takei Scientific Instrument Co, Niigata, Japan) and used it to measure the TFS-All, the TFS-great, and TFS-Lesser separately (detailed below). The overall procedure for measuring each TFS was in accordance with previous studies [16], [43]. First, the participants sat upright on the chair and their right foot was fixed on the ground of the device, with the hip and knee joints flexed at 90° and the ankle joint in a neutral position (90° plantarflexed) (Fig. 1a). The toe(s) intended for force production were then placed on a fixed and angle-adjustable sensor plate. As such, all toes were placed on the angle-adjustable sensor plate for TFS-All (Fig. 1b), the great toe only for TFS-Great (Fig. 1c), and the lesser toes for TFS--Lesser (Fig. 1d). For the latter two measurements, the toe(s) not intended to produce force (lesser toes for TFS-Great and great toe for TFS-Lesser) were placed on another metallic plate mounted outside of the device to avoid touching the sensor plate (Fig. 1c and d). In all TFS measurements, the angle-adjustable sensor plate was placed at 45° of dorsiflexion at the MTP joint, in accordance with previous studies [16], [43]. Previous reports have shown that the highest TFS values were determined at 45° of dorsiflexion at the MTP joint and 90° of dorsiflexion at the ankle joint angles in all cases when TFS was produced by all toes [9], the great toe [33], and lesser toes [33]. To avoid extraneous movements, the ankle and forefoot were fixed on the ground of the device using Velcro straps. To measure each TFS, the participants were instructed to cross their arms in front of their chest and press down the sensor plate as strongly as possible with the toes defined above, without any extraneous movements. During the measurements of the TFS-great and TFS-Lesser, the participants were required to pay attention only to the toe(s) intended for force production and not to produce force with the non-intended toes. They were further instructed not to lift any toes not intended for force production from the metallic plate in all the tests. Two or three trials of submaximal force outputs for the familiarization procedures were conducted before the measurements. After familiarization trials with at least a 3-minute rest period, the participants performed the task with the maximal force for at least 3 seconds. The maximum effort trials were repeated twice, with a rest period of at least 1 minute. The largest value was used for further analyses. The ICC of the two test trials were calculated to assess the inter-rater repeatability of each TFS measurement. The ICC (1, 2) was 0.98 for TFS-All, 0.98 for TFS-Great, and 0.97 for TFS-Lesser. In addition, the ICC of each TFS measurement, repeatedly performed three times for each 2–5 days apart with the same procedure, was examined in another experiment involving 11 healthy young males. The ICC (1, 3) satisfied the criteria of repeatability [15]: 0.81 for TFS-All, 0.79 for TFS-Great, and 0.87 for TFS-Lesser.

Statistical analysis

Descriptive data are presented as means ± SDs. The normality of each data was tested using the Kolmogorov–Smirnov test and confirmed to be normally distributed. A one-way repeated measures analysis of variance (ANOVA) followed by a post hoc Bonferroni test was conducted on three TFS values to compare between conditions (i.e., TFS-All, TFS-Great, and TFS-Lesser). Cohen's *d* effect size was calculated for between-condition differences, and the strength of this effect size was interpreted as follows: ≥ 0.80 was large, 0.50 to 0.79 medium, 0.20 to 0.49 weak and < 0.20 trivial [20]. In addition, Pearson's correlation coefficients were computed to examine the relationships between the TFS and $ACSA_{max}$ of each individual muscle or muscle group. Moreover, stepwise mul-

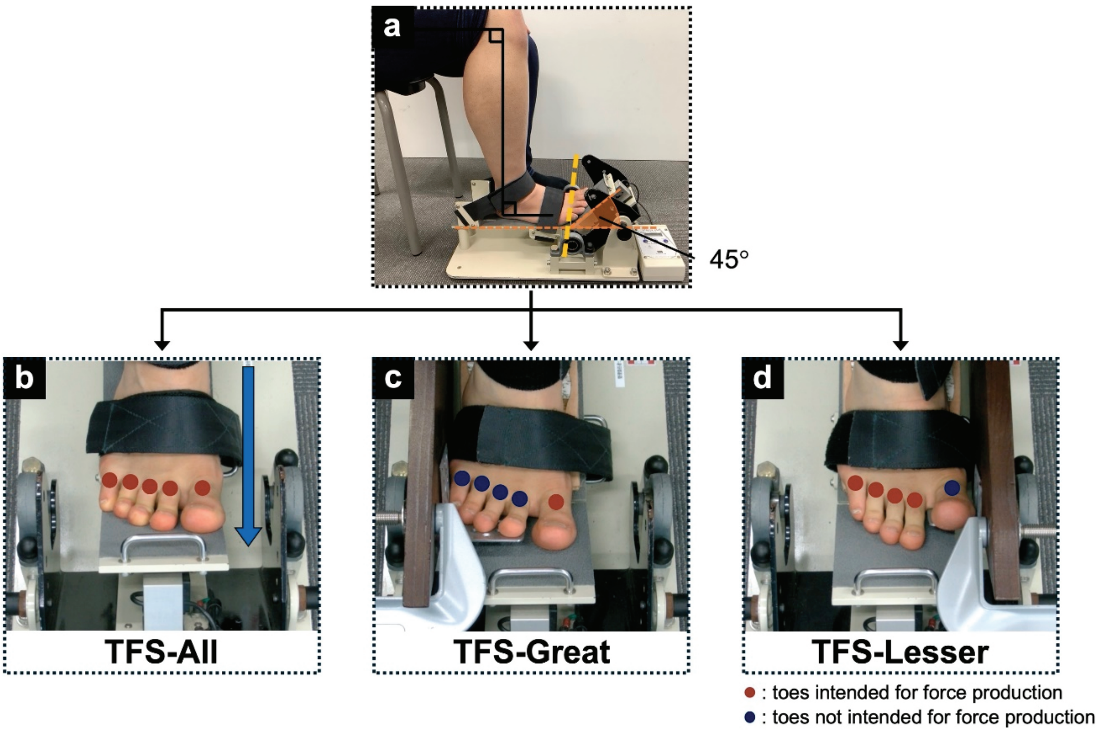

Fig. 1. Measurement of three types of toe flexor strength (TFS) using the custom-made toe push dynamometer. Panel a: lateral view of TFS measurement. The yellow dotted line indicates the horizontal axis of the metatarsophalangeal joint. Panel b, c, and d indicate the toes setting for measuring TFS produced by all toes (TFS-All), the great toe (TFS-Great), and lesser toes (TFS-Lesser), respectively. The blue arrow in the Panel b indicates the direction of pushing the sensor plate by each toe intended for force production

tiple liner regression analysis was performed by using each of three TFS (TFS-All, TFS-Great, and TFS--Lesser) as a dependent variable and $ACSA_{max}$ values of the muscles that were significantly correlated with each corresponding TFS as independent variables. The level of significance was set at $P < 0.05$. All statistical analyses were conducted using SPSS (version 27.0; IBM Co., USA).

3. Results

TFS values significantly differed among the conditions (Table 1, Fig. 2), with TFS-All greater than TFS--Great (Cohen's d = 1.75) and TFS-lesser (Cohen's d = 3.37), and TFS-Great greater than TFS-lesser (Cohen's d = 2.09) (all $P < 0.001$).

Table 1. Values of the maximum toe flexor strength produced by all toes (TFS-All), the great toe (TFS-Great), and lesser toes (TFS-Lesser)

	Mean ± SD	Range
TFS-All (N)	197.5 ± 40.2	111.7–289.1
TFS-Great (N)	138.2 ± 26.1	93.1–187.2
TFS-Lesser (N)	85.9 ± 24.1	45.1–129.4

Values are expressed as mean ± standard diviation (SD). TFS-All – toe flexor strength produced by all toes; TFS-Great – toe flexor strength produced by the great toe; TFS-Lesser – toe flexor strength produced by the lesser toes.

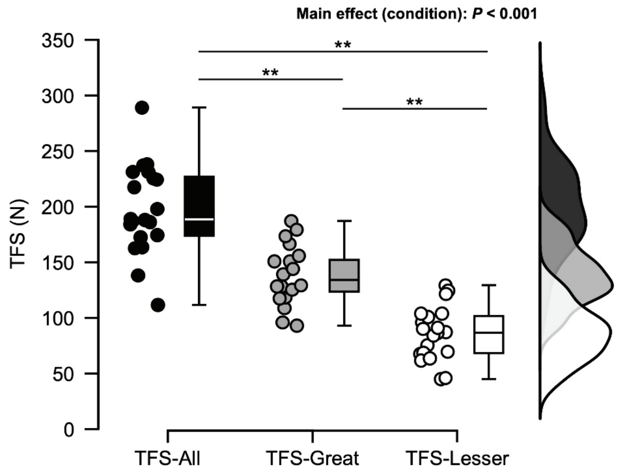

Fig. 2.Comparison of toe flexor strength (TFS) value among three conditions. Circle plots represent individual data, and box-and-whisker plots are median (interquartile range and max/min). The distribution of TFS value in each condition are shown as Raincloud plots. ** – Significant difference between conditions ($P < 0.01$)

$ACSA_{max}$ values for individual muscles and muscle groups of toe flexors are shown in Table 2. In Table 3, the Pearson's correlation coefficients between each TFS and $ACSA_{max}$ of each individual muscle or muscle group are summarized. TFS-All was significantly correlated with the $ACSA_{max}$ of ADDH-TH and FHB. As a result of stepwise multiple liner regression analysis, the $ACSA_{max}$ of the two muscles were selected as significant contributors for TFS-All: TFS-All (N) = 76.85 × [ADDH-TH (cm^2)] + 29.54 × [FHB (cm^2)] + 0.51

Table 2. $ACSA_{max}$ values for individual muscles and muscle groups in toe flexor muscles

	Mean ± SD	Range
Plantar intrinsic foot muscles [cm^2]		
All analyzed plantar intrinsic foot muscles	28.30 ± 3.20	22.68–33.25
Intrinsic great toe flexors	12.02 ± 1.35	9.18–14.43
ABDH	3.37 ± 0.66	1.91–4.48
ADDH-OH	3.86 ± 0.41	3.18–4.53
ADDH-TH	1.17 ± 0.24	0.77–1.67
FHB	3.61 ± 0.59	2.95–4.89
Intrinsic lesser toes flexors	16.28 ± 2.03	13.20–20.25
ABDM	3.31 ± 0.52	2.51–4.33
FDB	2.71 ± 0.43	1.91–3.45
FDM	1.49 ± 0.31	0.96–1.99
INT	6.73 ± 0.94	5.19–8.27
QP	2.04 ± 0.30	1.51–2.57
Extrinsic toe flexors [cm^2]	7.34 ± 1.15	5.53–9.63
FHL	5.40 ± 0.92	3.93–6.80
FDL	1.94 ± 0.42	1.14–2.82

Values are expressed as mean ± standard diviation (SD). ABDM – abductor digiti minimi, ABH – abductor hallucis, $ACSA_{max}$ – maximal anatomical cross-sectional area, ADDH-OH – adductor hallucis oblique head, ADDH-TH – adductor hallucis transverse head, FDB – flexor digitorum brevis, FDL – flexor digitorum longus, FHB – flexor hallucis brevis, FHL – flexor hallucis longus, QP – quadratus plantae.

Table 3. Pearson's correlation coefficients between the TFS and $ACSA_{max}$ of each individual muscle or muscle groups

	TFS-All		TFS-Great		TFS-Lesser	
	r	*P*	*r*	*P*	*r*	*P*
Plantar intrinsic foot muscles						
All analyzed plantar intrinsic foot muscles	0.379	0.099	0.030	0.900	0.219	0.354
Intrinsic great toe flexors	0.372	0.106	0.057	0.810	0.145	0.543
ABDH	0.166	0.485	–0.118	0.619	0.199	0.401
ADDH-OH	–0.178	0.453	–0.166	0.485	–0.171	0.471
ADDH-TH	**0.576**	**0.008**	0.255	0.278	0.220	0.352
FHB	**0.559**	**0.010**	0.276	0.239	0.139	0.559
Intrinsic lesser toes flexors	0.350	0.130	0.009	0.969	0.249	0.290
ABDM	0.293	0.210	–0.031	0.897	0.040	0.866
FDB	0.315	0.176	–0.057	0.813	0.028	0.907
FDM	0.439	0.053	0.012	0.959	0.083	0.727
INT	0.302	0.196	0.106	0.656	**0.481**	**0.032**
QP	0.021	0.930	–0.149	0.531	–0.013	0.955
Extrinsic toe flexors	0.314	0.177	0.367	0.111	–0.164	0.488
FHL	0.214	0.365	0.335	0.149	–0.231	0.328
FDL	0.391	0.088	0.272	0.247	0.053	0.823

ABDM – abductor digiti minimi, ABH – abductor hallucis, ADDH-OH – adductor hallucis oblique head, ADDH-TH – adductor hallucis transverse head, FDB – flexor digitorum brevis, FDL – flexor digitorum longus, FHB – flexor hallucis brevis, FHL – flexor hallucis longus, INT – plantar/dorsal interosseous, QP – quadratus plantae, TFS-All – toe push strength produced by all toes, TFS-Great – toe push strength produced by the great toe, TFS-Lesser – toe push strength produced by lesser toes.

(adjusted R^2 = 0.443). TFS-Great and TFS-Lesser were not significantly correlated with the $ACSA_{max}$ of any analyzed muscles or muscle groups, except that TFS--Lesser was significantly related to INT. However, a significant regression equation for TFS-Lesser was not produced by the stepwise multiple regression analysis with $ACSA_{max}$ of INT as the independent variable.

4. Discussion

This study was the first case to investigate how TFS developed under different conditions of the toe(s) intended for force production (i.e., TFS-All, TFS-Great, and TFS-Lesser) is associated with the size of individual toe flexor muscles. As expected, the greatest TFS value was observed in TFS-All, followed by TFS-Great and TFS-Lesser (Table 1 and Fig. 2), indicating that the magnitude of TFS is dependent on the toe(s) intended for force production. The main findings were that TFS-All was associated with the size of not only FHB (a great toe flexor) but also ADDH-TH (a great toe adductor), and that neither TFS-Great nor TFS-Lesser was associated with the size of the muscles specialized in each corresponding toe flexion. The current results mainly denied our hypothesis and indicate that the magnitude of TFS, which depends on the toe(s) intended for force production, is not associated with the size of the muscles anatomically specialized in each toe flexion.

TFS-All was significantly correlated with the $ACSA_{max}$ of FHB, which is specialized in the great flexion, and ADDH-TH, which mainly adducts and supplementarily flexes the great toe (Table 3). Moreover, the stepwise multiple liner regression analysis showed that the $ACSA_{max}$ values of the two plantar intrinsic foot muscles explained 44% of the variance in TFS-All. This differed from the finding of Kusagawa et al. [18], in which the $ACSA_{max}$ of ADDH-OH was selected as the primary contributor to TFS-All measured using a toe grip dynamometer. This discrepancy might be attributed to the toe action and MTP joint position during TFS measurements. The present study measured TFS-All by using the toe push dynamometer, which requires the toe pushing action consisting of flexion at the MTP joint with minimum flexion of the interphalangeal (IP) joint [36]. Based on the difference in the anatomical insertion of the FHB and FHL, the former flexes the first MTP joint only, whereas the latter causes the flexion at the first MTP joint as well as IP joints [27]. A recent study [32] found that the muscle activities during TFS-All with a toe pushing action were more dependent on the FHB than the FHL in most participants, whereas those during TFS-All with a toe gripping action were significantly greater in FHL compared to FHB. These findings indicate that, compared to FHL, the anatomical function of FHB is more suitable for performing the toe pushing action, being required for producing TFS-All with a toe push dynamometer.

In terms of the MTP joint position during TFS-All measurement, the toe push dynamometer used in this study requires force production at the MTP joint in a dorsiflexed position [16], [43], while the toe grip dynamometer adopted in Kusagawa et al. [18] requires force production at the MTP joint in a plantarflexed position [16], [43]. It has been shown that TFS-All determined with a toe push dynamometer (MTP joint dorsiflexed) was greater than that with a toe grip dynamometer (MTP joint plantarflexed) [16], [32], and TFS-All increased with increasing dorsiflexion angle at the MTP joint [9], [33]. This is considered to be due to the length-tension relationship of toe flexor muscles [9], [32]. When the MTP joint is dorsiflexed, both FHB and FHL, which cross underneath the first metatarsal bone, one extended than ADDH-OH, which passes through the lateral side of the first metatarsal bone. Furthermore, it is likely that FHB would be more lengthened than FHL as a percentage of the resting length [32], because the FHL tendon cross underneath the FHB and attaches to the base of the first distal phalanx. Thus, it seems that FHB approaches the ascending limb of the length-tension relationship when producing TFS-All with a toe push dynamometer (MTP joint dorsiflexed position) and so could produce higher force than the ADDH-OH and FHL. In addition, Robb et al. [30] found that the peak of electromyographic activity in ADDH-TH, which runs along the anterior transverse arch in the forefoot, occurred at toe-off phases of walking, when increased force production was required across the forefoot with the dorsiflexed MTP joint. Thus, when attempting to produce force on the toes with the dorsiflexed MTP joint, it is likely that the ADDH-TH assists this by preventing metatarsal splaying through the medially oriented lever arm that anchors the hallux to the ground [30]. Taken together, the current results may be attributable to the fact that among toe flexor muscles, FHB and ADDH-TH are the most suitable muscle to produce TFS-All in terms of the MTP joint position and toe action required for producing force with a toe push dynamometer. More specifically, FHB and ADDH-TH may act as the main force generators in the hallux and stabilizers of the forefoot, respectively, during TFS-All measurement with a toe pushing action and dorsiflexed MTP joint.

No statistically significant correlations were found between TFS-Great/TFS-Lesser and $ACSA_{max}$ of any analyzed muscles, except for TFS-Lesser with INT (Table 3), which is not anatomically specialized in lesser toes flexion. Namely, INT mainly causes the abduction (dorsal interossei) or adduction (plantar interossei) of MTP joints, and supplementary resists the extension of MTP joints and flexion of IP joint [4], [27]. This unexpected result might be explained by the following two possibilities. First, it is possible that most of plantar intrinsic foot muscles cannot be fully or separately activated during the TFS-Great and TFS-Lesser production. Perez Olivera et al. [28] examined the magnitude of ABDH activation during maximal force output by a combination of abduction and flexion of the great toe. They reported that only a limited number of participants (23%) could voluntarily activate ABDH at more than 90% of the maximum activation level determined by the twitch interpolation technique, whereas the others (77%) voluntarily activated this muscle at approximately 70% on average (range of 36–83%) [28]. In addition, Gooding et al. [10] have shown that the second-to-fifth-toe extension exercise, which was designed to target the muscles attached to the great toe by stabilizing the great toe on the floor while extending the lesser toes, activated the FHB, ADDH-OH (both attached to the great toe), and ABDM (attached to the little toe). From these results, they suggested that foot exercises activate not only the target muscles but also other non-target muscles at a significant level [10]. These findings indicate that under voluntary contractions, the plantar intrinsic foot muscles cannot be fully and separately activated during TFS production by the great toe and lesser toes with the related muscles. Second, mechanical coupling of the tendons could explain the present results. A cadaveric study with 55 specimens and 110 legs observed mechanical connections between the tendons of the extrinsic toe flexors (i.e., FHL and FDL) in all cases [5]. Thus, it is likely that the FHL and FDL do not selectively cause the flexion of the great toe and lesser toes, respectively. Consequently, when producing TFS-Great and TFS-Lesser, muscle tension produced by the muscles related to the toes intended for force production may be distributed to other toes not intended for force production. In fact, it has been observed that when producing the force by a finger with peripheral tendon connections of finger muscles, other fingers, especially the adjacent finger not intended to produce force involuntarily, also produced a substantial amount of force [44]. Thus, no association between TFS-Great/TFS-Lesser and the size of any muscles may be explained by difficulty in maximally and separately activating individual toe flexors for neural/anatomical reasons during the TFS-Great and TFS--Lesser production.

This study has three limitations. First, we discussed the toe action, MTP joint position and the posture during TFS measurements in relation to the device utilized as the reasons for the unexpected results. However, we have no data on the TFS measured using other devices. Thus, further studies are needed to clarify the influences of differences in devices used for TFS determinations on the associations between the measured TFS and muscle size. Second, the results of this study suggest that the reduced activation level and mechanical tendon connections of toe flexor muscles might be the potential reasons why the size of the toe flexor muscles cannot explain the TFS production by the great toe and lesser toes. However, we have no data on the differences in the activated muscles during the development of the three types of TFS. Some studies have adopted T2-weighted MRI [10] and positron emission tomography [14] to determine which muscle(s) are activated during foot exercises with complex movements, such as the short-foot, towel-gathering and toe-spread-out exercises. Further studies applying such methods may clarify the contribution of individual toe flexor muscles to TFS production, depending on the toe(s) intended for force production. Third, this study only examined male university students. The reason for this was to avoid potential confounding influences of sex [17] and age-related [23] differences in the magnitude of the TFS and the size of the plantar intrinsic foot muscles. Further studies are warranted to determine whether the current findings can be generalized to other populations.

5. Conclusions

The size of two individual plantar intrinsic foot muscle, being anatomically specialized (FHB) and having assistive function (ADDH-TH) for the great toe flexion, are selected as significant contributors to TFS--All production by stepwise multiple liner regression analysis. However, TFS-Great and TFS-Lesser are not associated with the size of toe flexor muscles anatomically specialized in each corresponding toe flexion.

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References

[1] ABE T., TAYASHIKI K., NAKATANI M., WATANABE H., *Relationships of ultrasound measures of intrinsic foot muscle cross-sectional area and muscle volume with maximum toe flexor muscle strength and physical performance in young adults*, J. Phys. Ther. Sci., 2016, 28 (1), 14–19, DOI: 10.1589/jpts.28.14.

[2] BALSHAW T.G., MADEN-WILKINSON T.M., MASSEY G.J., FOLLAND J.P., *The Human Muscle Size and Strength Relationship: Effects of Architecture, Muscle Force, and Measurement Location*, Med. Sci. Sports Exerc., 2021, 53 (10), 2140–2151, DOI: 10.1249/MSS.0000000000002691.

[3] BLAZEVICH A.J., GILL N.D., ZHOU S., *Intra- and intermuscular variation in human quadriceps femoris architecture assessed in vivo*, J. Anat., 2006, 209 (3), 289–310, DOI: 10.1111/j.1469-7580.2006.00619.x

[4] DRAKE R.L., VOGL W., MITCHELL A.W.M., *Gray's anatomy for students*, 4th ed., Elsevier, 2020.

[5] EDAMA M., KUBO M., ONISHI H., TAKABAYASHI T., YOKOYAMA E., INAI T., WATANABE H., NASHIMOTO S., KAGEYAMA I., *Anatomical study of toe flexion by flexor hallucis longus*, Ann. Anat., 2016, 204, 80–85, DOI: 10.1016/j.aanat.2015.11.008.

[6] ENDO M., ASHTON-MILLER J.A., ALEXANDER N.B., *Effects of age and gender on toe flexor muscle strength*, J. Gerontol. A Biol. Sci. Med. Sci., 2002, 57 (6), M392–397, DOI: 10.1093/gerona/57.6.m392.

[7] FARRIS D.J., KELLY L.A., CRESSWELL A.G., LICHTWARK G.A., *The functional importance of human foot muscles for bipedal locomotion*, Proc. Natl. Acad. Sci. U.S.A, 2019, 116 (5), 1645–1650, DOI: 10.1073/pnas.1812820116.

[8] FUKUNAGA T., MIYATANI M., TACHI M., KOUZAKI M., KAWAKAMI Y., KANEHISA H., *Muscle volume is a major determinant of joint torque in humans*, Acta Physiol. Scand., 2001, 172 (4), 249–255, DOI: 10.1046/j.1365-201X.2001.00867.x.

[9] GOLDMANN J.P., BRÜGGEMANN G.P., *The potential of human toe flexor muscles to produce force*, J. Anat., 2012, 221 (2), 187–194, DOI: 10.1111/j.1469-7580.2012.01524.x.

[10] GOODING T.M., FEGER M.A., HART J.M., HERTEL J., *Intrinsic Foot Muscle Activation During Specific Exercises: A T2 Time Magnetic Resonance Imaging Study*, J. Athl. Train., 2016, 51 (8), 644–650, DOI: 10.4085/1062-6050-51.10.07.

[11] HASHIMOTO T., UENO K., OGAWA A., ASAMIZUYA T., SUZUKI C., CHENG K., TANAKA M., TAOKA M., IWAMURA Y., SUWA G., IRIKI A., *Hand before foot? Cortical somatotopy suggests manual dexterity is primitive and evolved independently of bipedalism*, Philos. Trans. R Soc. Lond. B Biol. Sci., 2013, 368 (1630), 20120417, DOI: 10.1098/rstb.2012.0417.

[12] HAXTON H.A., *Absolute muscle force in the ankle flexors of man*, J. Physiol., 1944, 103 (3), 267–273, DOI: 10.1113/jphysiol.1944.sp004075.

[13] IKAI M., FUKUNAGA T., *Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement*, Int. Z. Angew. Physiol., 1968, 26 (1), 26–32, DOI: 10.1007/bf00696087.

[14] KANAYAMA T., NAKASE J., MOCHIZUKI T., ASAI K., YOSHIMIZU R., KIMURA M., KINUYA S., TSUCHIYA H., *Evaluation of skeletal muscle activity during foot training exercises using positron emission tomography*, Sci. Rep., 2022, 12 (1), 7076, DOI: 10.1038/s41598-022-11202-y.

[15] KOO T.K., LI M.Y., *A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research*,

J. Chiropr. Med., 2016, 15 (2), 155–163, DOI: 10.1016/j.jcm.2016.02.012.

[16] KURIHARA T., TERADA M., NUMASAWA S., KUSAGAWA Y., MAEO S., KANEHISA H., ISAKA T., *Effects of age and sex on association between toe muscular strength and vertical jump performance in adolescent populations*, PloS One, 2021, 16 (12), e0262100, DOI: 10.1371/journal.pone.0262100.

[17] KURIHARA T., YAMAUCHI J., OTSUKA M., TOTTORI N., HASHIMOTO T., ISAKA T., *Maximum toe flexor muscle strength and quantitative analysis of human plantar intrinsic and extrinsic muscles by a magnetic resonance imaging technique*. J. Foot Ankle Res., 2014, 7, 26, DOI: 10.1186/1757-1146-7-26.

[18] KUSAGAWA Y., KURIHARA T., MAEO S., SUGIYAMA T., KANEHISA H., ISAKA T., *Associations between the size of individual plantar intrinsic and extrinsic foot muscles and toe flexor strength*, J. Foot Ankle Res., 2022, 15 (1), 22, DOI: 10.1186/s13047-022-00532-9.

[19] KUSAGAWA Y., KURIHARA T., MAEO S., SUGIYAMA T., KANEHISA H., ISAKA T., *Associations of muscle volume of individual human plantar intrinsic foot muscles with morphological profiles of the foot*, J. Anat., 2022, 241 (6), 1336–1343, DOI: 10.1111/joa.13753.

[20] LAKENS D., *Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs*, Frontiers in Psychology, 2013, 4, 863, DOI: https://doi.org/10.3389/fpsyg.2013.00863

[21] LATEY P.J., BURNS J., NIGHTINGALE E.J., CLARKE J.L., HILLER C.E., *Reliability and correlates of cross-sectional area of abductor hallucis and the medial belly of the flexor hallucis brevis measured by ultrasound*, J. Foot Ankle Res., 2018, 11 (1), 1–11, DOI: 10.1186/s13047-018-0259-0.

[22] MATSUNO S., YOSHIMURA A., YOSHIIKE T., MORITA S., FUJII Y., HONMA M., OZEKI Y., KURIYAMA K., *Toe grip force of the dominant foot is associated with fall risk in community-dwelling older adults: a cross-sectional study*, J. Foot Ankle Res., 2022, 15 (1), 42, DOI: 10.1186/s13047-022-00548-1.

[23] MICKLE K.J., ANGIN S., CROFTS G., NESTER C.J., *Effects of age on strength and morphology of toe flexor muscles*, J. Orthop. Sports Phys. Ther., 2016, 46 (12), 1065–1070, DOI: 10.2519/jospt.2016.6597.

[24] MICKLE K.J., MUNRO B.J., LORD S.R., MENZ H.B., STEELE J.R., *ISB Clinical Biomechanics Award 2009: toe weakness and deformity increase the risk of falls in older people*, Clin. Biomech., Bristol, Avon., 2009, 24 (10), 787–791, DOI: 10.1016/j.clinbiomech.2009.08.011.

[25] MISU S., DOI T., ASAI T., SAWA R., TSUTSUMIMOTO K., NAKAKUBO S., YAMADA M., ONO R., *Association between toe flexor strength and spatiotemporal gait parameters in community-dwelling older people*, J. Neuroeng. Rehabil., 2014, 11 (1), 1–7, DOI: 10.1186/1743-0003-11-143.

[26] MORITA N., YAMAUCHI J., KURIHARA T., FUKUOKA R., OTSUKA M., OKUDA T., ISHIZAWA N., NAKAJIMA T., NAKAMICHI R., MATSUNO S., KAMIIE S., SHIDE N., KAMBAYASHI I., SHINKAIYA H., *Toe flexor strength and foot arch height in children*, Med. Sci. Sports Exerc., 2015, 47 (2), 350–356, DOI: 10.1249/MSS.0000000000000402.

[27] NEUMANN D.A., *Kinesiology of the musculoskeletal system: foundations for rehabilitation*, Elsevier, Mosby, 2017.

[28] PEREZ OLIVERA A.L., SOLAN M.C., KARAMANIDIS K., MILEVA K.N., JAMES D.C., *A voluntary activation deficit in m. abductor hallucis exists in asymptomatic feet*, J. Biomech., 2022, 130, 110863, DOI: 10.1016/j.jbiomech.2021.110863.

[29] RIDGE S.T., MYRER J.W., OLSEN M.T., JURGENSMEIER K., JOHNSON A.W., *Reliability of doming and toe flexion testing to quantify foot muscle strength*, J. Foot Ankle Res., 2017, 10 (1), 1–7, DOI: 10.1186/s13047-017-0237-y.

[30] ROBB K.A., MELADY H.D., PERRY S.D., *Fine-wire electromyography of the transverse head of adductor hallucis during locomotion*, Gait Posture., 2021, 85, 7–13, DOI: 10.1016/j.gaitpost.2020.12.020.

[31] ROWLEY K.M., JARVIS D.N., KURIHARA T., CHANG Y.J., FIETZER A.L., KULIG K., *Toe Flexor Strength, Flexibility and Function and Flexor Hallucis Longus Tendon Morphology in Dancers and Non-Dancers*, Med. Probl. Perform Art., 2015, 30 (3), 152–156, DOI: 10.21091/mppa.2015.3029.

[32] ROWLEY M., KURIHARA T., ORTIZ-WEISSBERG D., KULIG K., *Contributions of flexor hallucis longus and brevis muscles to isometric toe flexor force production*, Acta Bioeng. Biomech., 2023, 25 (1), DOI: 10.37190/ABB-02222-2023-02.

[33] SAEKI J., IWANUMA S., TORII S., *Force generation on the hallux is more affected by the ankle joint angle than the lesser toes: An in vivo human study*, Biology, 2021, 10 (1), 1–8, DOI: 10.3390/biology10010048.

[34] SAEKI J., TOJIMA M., TORII S., *Relationship between navicular drop and measuring position of maximal plantar flexion torque of the first and second-fifth metatarsophalangeal joints*, J. Phys. Ther. Sci., 2015, 27 (6), 1795–1797, DOI: 10.1589/jpts.27.1795.

[35] SMITH R.E., LICHTWARK G.A., KELLY L.A., *The energetic function of the human foot and its muscles during accelerations and decelerations*, J. Exp. Biol., 2021, 224 (13), jeb242263, DOI: 10.1242/jeb.242263.

[36] SOYSA A., HILLER C., REFSHAUGE K., BURNS J., *Importance and challenges of measuring intrinsic foot muscle strength*, J. Foot Ankle Res., 2012, 5 (1), 29, DOI: 10.1186/1757-1146-5-29.

[37] SPINK M.J., FOTOOHABADI M.R., MENZ H.B., *Foot and ankle strength assessment using hand-held dynamometry: reliability and age-related differences*, Gerontology, 2010, 56 (6), 525–532, DOI: 10.1159/000264655.

[38] TOURILLON R., MICHEL A., FOURCHET F., EDOUARD P., MORIN J.B., *Human foot muscle strength and its association with sprint acceleration, cutting and jumping performance, and kinetics in high-level athletes*, J. Sports Sci., 2024, 42 (9), 814–824, DOI: 10.1080/02640414.2024.2367365.

[39] URITANI D., FUKUMOTO T., MATSUMOTO D., *Intrarater and interrater reliabilities for a toe grip dynamometer*, J. Phys. Ther. Sci., 2012, 24 (8), 639–643, DOI: 10.1589/jpts.24.639.

[40] URITANI D., FUKUMOTO T., MATSUMOTO D., SHIMA M., *Reference values for toe grip strength among Japanese adults aged 20 to 79 years: A cross-sectional study*, J. Foot Ankle Res., 2014, 7 (1), 1–6, DOI: 10.1186/1757-1146-7-28.

[41] URITANI D., FUKUMOTO T., MATSUMOTO D., SHIMA M., *Associations between toe grip strength and hallux valgus, toe curl ability, and foot arch height in Japanese adults aged 20 to 79 years: A cross-sectional study*, J. Foot Ankle Res., 2015, 8 (1), 4–9, DOI: 10.1186/s13047-015-0076-7.

[42] YAMAUCHI J., KOYAMA K., *Importance of toe flexor strength in vertical jump performance*, J. Biomech., 2020, 7, 104, 109719, DOI: 10.1016/j.jbiomech.2020.109719.

[43] YUASA Y., KURIHARA T., ISAKA T., *Relationship between Toe Muscular Strength and the Ability to Change Direction in Athletes*, J. Hum. Kinet., 2018, 64 (1), 47–55, DOI: 10.1515/hukin-2017-0183.

[44] ZATSIORSKY V.M., LI Z.M., LATASH M.L., *Enslaving effects in multi-finger force production*, Exp. Brain Res., 2000, 131 (2), 187–195, DOI: 10.1007/s00221990026.