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Contributions of flexor hallucis longus and brevis muscles to isometric toe flexor force production

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Purpose: Morphological differences between the two primary great toe flexors – flexor hallucis longus (FHL) and flexor hallucis brevis (FHB) – likely drive differences in how these muscles contribute to functional toe flexor torque production. The aim of the study was to investigate FHL and FHB activation in two isometric toe flexion tasks – one called a "toe-pushing" task with the metatarsophalangeal (MTP) joints dorsiflexed and the interphalangeal (IP) joints in neutral and another called a "toe-gripping" task with the MTP joints in neutral and flexed IP joints. *Methods*: Twenty participants' FHL and FHB muscles were instrumented with intramuscular electromyography electrodes. Muscle activation was normalized to a maximum voluntary contraction and compared between the two isometric toe flexor force production tasks. *Results*: Overall, participants utilized these two toe flexors completely differently in the two tasks. In the toe-gripping task, the FHL was activated to a much greater extent than the FHB. In fact, 18 our of 20 participants activated FHL at more than 70% maximum voluntary contraction and half of participants activated FHB at less than 10%. In contrast, muscle activation during the toe-pushing task appeared more reliant on the FHB for most participants. *Conclusions*: Different contributions from the FHL and FHB to toe flexor force production in these two tasks are potentially driven by differences in muscle functional length among other factors. These findings help to inform the selection of rehabilitation and training exercises meant to preferentially target intrinsic or extrinsic foot musculature.

Key words: *intrinsic foot muscle, extrinsic foot muscle, hallux, foot, ankle*

1. Introduction

The hallux (great toe) achieves plantar flexion and dorsiflexion motions in the sagittal plane through two articulations, one between the head of the first metatarsus and the base of the proximal phalanx (metatarsophalangeal [MTP] joint), and another between the head of the proximal phalanx and the base of the distal phalanx (interphalangeal [IP] joint). Two of the muscles that cross the plantar aspects of these joints are the flexor hallucis longus (FHL) and the flexor hallucis brevis (FHB), the latter of which has both medial and lateral heads located on either side of the FHL tendon. Both muscles impart a plantar flexor torque at the MTP joint, while the FHL muscle also imparts plantar flexor torques at the IP joint and the ankle joint. These different functions arise due to the differences in muscle origin and insertion locations. The FHB originates on the cuneiforms and inserts onto the base of the proximal phalanx through two sesamoid bones, therefore, crossing only the MTP joint. The FHL originates on the posterior fibula and inserts onto the base of the distal phalanx, therefore crossing the ankle, MTP, and IP joints [3], [12] (Fig. 1).

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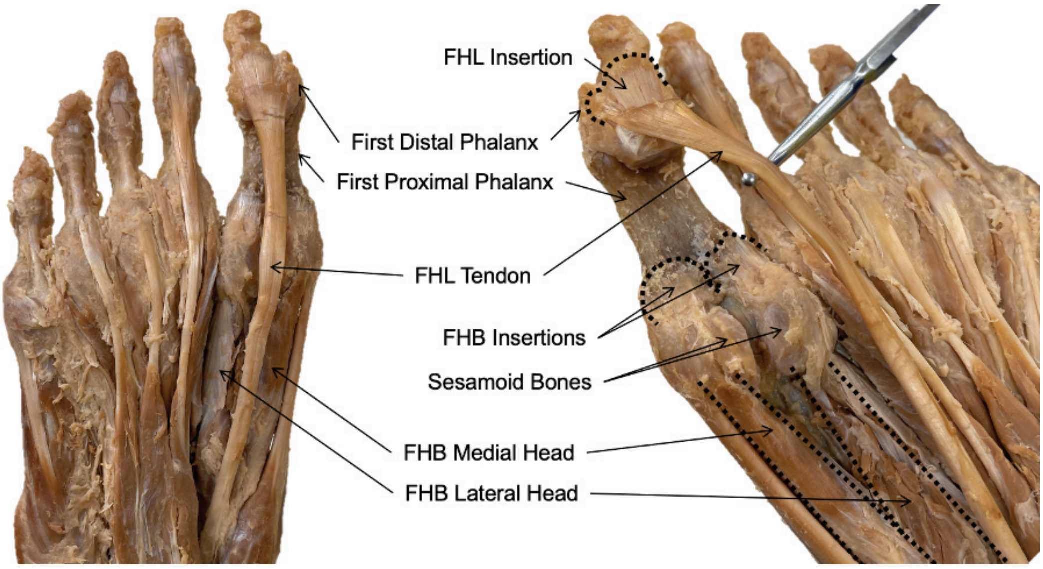

Fig. 1. Plantar view of the insertions of the flexor hallucis longus (FHL) and flexor hallucis brevis (FHB) muscles on the first distal phalanx and the first proximal phalanx, respectively

Functionally, we know that these muscles activate in distinct but coordinated ways depending on ankle and MTP joint positions. In static weight-bearing postures, both FHB and FHL activations are positively correlated with foot longitudinal arch deformation [5]. When balancing on one foot, FHB exhibits increased activation compared to bipedal standing, and when balancing on the toes, both FHB and FHL show increased activation [17]. Further, when testing associations between toe flexor strength and dynamic functional movements tasks, MTP joint position matters. Yuasa et al. [20] found an association between athletes' agility and toe flexor strength measured in a dorsiflexed MTP position but not when measured in a plantar flexed MTP joint position. The opposite was true when testing associations with maximum vertical jump height [6]. Clearly, the interaction of ankle and MTP joint postures influences contributions from FHL and FHB in a complex and functional way. The hallux may be unique among the toes in this regard since hallux force production is more affected by ankle joint position than forces produced by the lesser toes [18].

An understanding of which muscles contribute to toe flexor strength in different foot and ankle postures is clinically important. Intrinsic foot muscle weakness is linked to the development of multiple pathologies including hallux valgus, hammer toe and heel pain [19]. There is little agreement, however, about how much strength is required to prevent or treat these conditions. Further, we do not have valid ways to differentially measure intrinsic and extrinsic foot muscle strength. A limited number of studies have attempted to differentiate the roles of FHL and FHB in toe flexor force production in different MTP joint positions. Many of these, however, have used muscle size or volume as a surrogate measure of muscle activation, which is not a direct measure of activation [7], [8], [13]. In order to improve clinical assessment and intervention we, therefore, must further disambiguate the contributions of extrinsic (e.g., FHL) and intrinsic (e.g., FHB) muscles to toe flexor strength. Utilizing electromyographic (EMG) recordings of extrinsic and intrinsic foot muscles concurrently with toe flexor strength assessments that position the toes in different functional postures (e.g., plantar flexed or dorsiflexed MTP joint) should help to elucidate these contributions.

The purpose of this study was to investigate activation amplitudes of FHL and FHB muscles during isometric toe flexor force production by comparing toe-gripping strength with the MTP joint in a plantar flexed position and toe-pushing force with the MTP joint in the dorsiflexed position. We hypothesized that imparting an isometric push force while maintaining a neutral IP joint would primarily depend on FHB recruitment, while an isometric gripping force with the MTP and IP joints plantar flexed would involve activation of both the FHB and FHL.

2. Materials and methods

Participants and Instrumentation

Twenty young adults (7 Males, 13 Females; Age: 27.7 ± 5.6 years; Weight: 68.1 ± 15.1 kg; BMI: 23.3

± 3.0 kg/m^2) without any pain or lower extremity injury in the past six months and no history of bleeding disorders volunteered for the study according to guidelines by the Institutional Review Board. Participants were instructed to refrain from using NSAIDs for 48 hours prior to testing. Paired fine-wire intramuscular electrodes (50 μm Ni-Cr alloy wires with nylon insulation, with the distal 2 mm stripped of insulation and bent into a hook loaded into sterilized 25 gauge 1.5 inch hypodermic needles) were inserted into the FHB and FHL muscles according to guidelines in published literature [4], [15]. Electrode placement was guided with ultrasonography (Sonoline Antares with VFX 13-5 linear array transducer, Siemens Medical Solutions USA, Inc., Malvern, PA) and confirmed using mild electrical stimulation and manual muscle testing. Instrumentation was performed on the side contralateral to each participant's preferred kicking limb. EMG data were collected using a wireless Noraxon system (TeleMyo 586 Desktop DTS unit; Scottsdale, AZ) sampled at 3000 Hz. EMG signals were bandpass filtered between 30 Hz and 1000 Hz using a fourth-order, zero-lag Butterworth filter. Root mean square (RMS) signal amplitude was calculated over a three-second epoch to acquire a maximum activation amplitude for each trial. Participants were asked to produce maximum voluntary contractions (MVCs) for a series of manual muscle tests (MMTs) including dorsiflexion, inversion, eversion of the ankle and abduction of the first digit.

Protocol

Participants completed two toe flexor maximal force production tasks. For the toe-pushing task with the MTP in a dorsiflexed position, toe flexor strength was measured using a custom dynamometer (T.K.K. 1268 Takei Scientific Instrument Co., Ltd., Niigata, Japan). Measurements were performed in an upright seated position with arms across the chest, the ankle joint secured at neutral position, the participant's foot flat, and MTP joints in 60° of extension (Fig. 2b). The instructions given were to "press the plate down as hard and as quickly as possible and keep that pressure for three seconds". Participants were allowed to practice this task 2–3 times before the measurements. Then, each participant performed two maximal effort MTP plantar flexion contractions into the dynamometer for at least three seconds. Force exerted and muscle activation were averaged across the two trials. Force measured was normalized to body mass.

For the toe-gripping task with the MTP and IP joints allowed to plantar flex, a toe-gripping dynamometer was used (T.K.K. 3365, Takei Scientific Instrument Co., Niigata). Measurements were performed in an upright seated position with the arms across the chest, the ankle joint positioned in neutral, the participant's foot flat, and with the IP joints gripping the bar (Fig. 2a). Participants were instructed to grip the bar using all their toes without any extraneous movements of the foot, ankle out lower extremity. The instructions given were to "grip and pull the bar as hard and as quickly as possible and keep that pressure for three seconds". Participants were allowed to practice this task 2–3 times before the measurements. Then, each participant completed four trials with maximal effort for at least three seconds each. In pilot testing, we discovered this task took more attempts to achieve stable force production, so additional trials were collected and averaged compared to the toe-pushing task. The device includes a digital

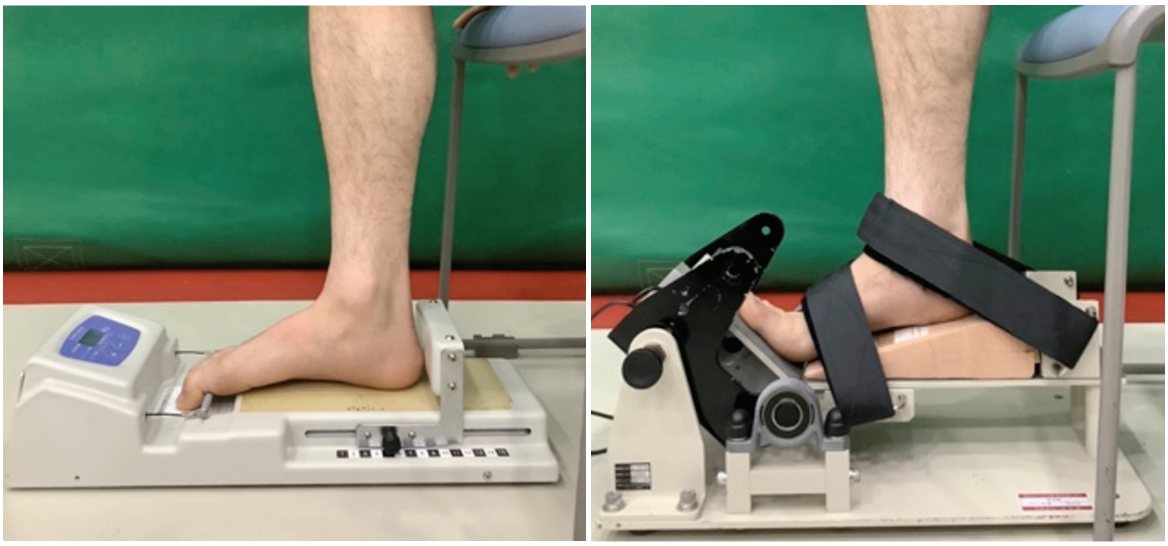

Fig. 2. Toe-gripping (left) and toe-pushing (right) tasks

display of force data, but participants were instructed not to observe the display. Force exerted and muscle activation were averaged across the four trials. Force measured was normalized to body mass.

Processing and analysis

Due to the wide variety of MMT tasks that participants performed during the data acquisition, we chose to normalize the muscle activation during the dynamometry tasks to the maximum activation during the two toe flexor strength dynamometer tasks or during any of the four MMTs in which a maximal activation would make sense for that muscle. Two additional normalization procedures were tested, including one procedure using only the two toe flexor strength dynamometer task trials and one procedure using any MMT. Those data are reported in the Supplementary Material. Major conclusions were not affected by the choice of normalization procedure.

Data were screened for outliers using the criterion of more than 1.5 times the interquartile range. Shapiro–Wilk tests revealed that only the normalized force data came from normal distributions. Thus, paired *t*-tests were used to compare the normalized forces across the dynamometer tasks while Wilcoxon signed rank tests were used for the normalized muscle activation magnitudes (for both FHL and FHB) across the two tasks. Hedge's G effect size was calculated only for the normally-distributed force data. We report both *p*-values and the 95% confidence interval for the effect size (force data) and median difference between tasks (muscle activation). Pearson's correlation was performed to assess the association between the normalized force data from the two tasks. A simple linear regression was performed solely for the purpose of plotting a line of best fit for the force-force data. Reliability of the measurements was assessed with a Two-Way Mixed Intra-Class Correlation (ICC) coefficient for absolute agreement. Data are available via Open Science Framework.

3. Results

Force

The cohort was able to produce an average force of 12.6 ± 4.78 kg (ICC = 0.905) with the MTP plantar flexed (toe-gripping) and an average of 11.0 ± 5.1 kg (ICC = 0.848) with the MTP dorsiflexed (toe-pushing) (Table 1). After normalization, these forces were equivalent to 18.6 ± 5.92% of body mass (ICC = 0.856) (MTP plantar flexed, toe-gripping) and 15.96 ± 7.74% body mass (ICC = 0.927) (MTP dorsiflexed, toe-pushing). One participant was identified as an outlier in the normalized force data for the toe-pushing task based on criteria described previously. The normalized force with the MTP plantar flexed was significantly greater than that with the MTP dorsiflexed regardless of whether the outlier was removed from the paired *t*-test analysis (effect size with all participants [95% confidence interval (CI) for effect size] = 0.37 [0.098, 0.64], $p = 0.008$; effect size with outlier removed [95% CI] = 0.49 [0.16, 0.82], $p = 0.004$). The positive correlation between the normalized force magnitudes from each task when the outlier was removed from the analysis (r with all participants [95% CI] = 0.64 [0.41, 0.79], $p < 0.001$; r with outlier removed [95% CI] = 0.51 [0.23, 0.71], $p = 0.001$) is illustrated in Fig. 3.

Muscle activation

Activation amplitudes for each muscle during each dynamometer task are shown in Fig. 4. The cohort's mean activations and ICC values are presented in Table 1. The toe-pushing task in MTP dorsiflexion elicited significantly greater FHB activation compared to the toe-gripping task where the MTP was in plantar flexion (Median difference [95% CI] = –32.72% MVC [–51.13, –10.81], $p = 0.001$). In stark contrast to the FHB, the FHL displayed significantly greater activation during the toe-gripping task where MTP plantarflexion was allowed (Median difference [95% CI] = 38.42% MVC [26.56, 48.14], $p < 0.001$). Thus, the two dynamometer tasks displayed unique abilities to recruit the FHB (toe-pushing task) versus the FHL (toe-gripping task).

4. Discussion

The purpose of this study was to compare FHL and FHB muscle activation amplitudes in a toe-pushing task with MTP dorsiflexion and in a toe-gripping task where the MTP and IP joints were allowed to plantar flex. First, there was a difference in toe flexor force production between the two tasks, but this difference was small (2%) and, in fact, there was a moderate-strong positive association between force measured in each task. Despite this consistency in force production, participants utilized the FHL and FHB completely differently in the two tasks. In the toe-gripping task with MTP and IP plantar flexion allowed, the FHL was activated to a much greater extent than the FHB. In fact, 18/20 participants activated FHL at >70% MVC and half of participants activated FHB at

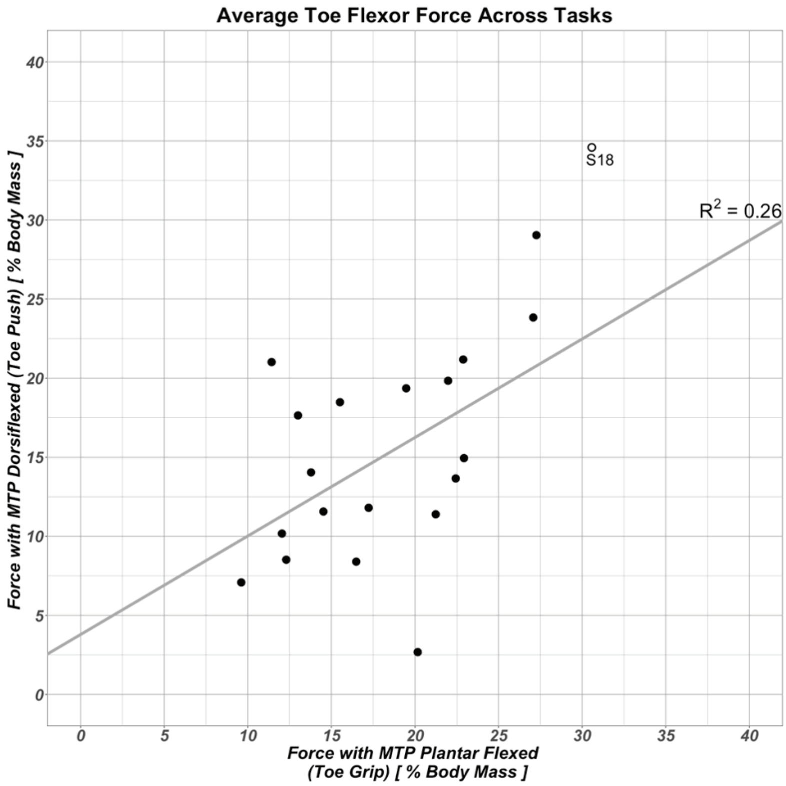

Fig. 3. Scatterplot displaying the force from the plantar flexed MTP task (*x*-axis) and dorsiflexed MTP task (*y*-axis), along with the line of best fit and corresponding R^2 value. The displayed correlation and R^2 were calculated after removing an outlier in the dorsiflexed MTP data; this data point is displayed as an open circle (S18) in the figure. The force from the plantar flexed MTP task explained approximately 26% of the variance in the force data from the dorsiflexed MTP task

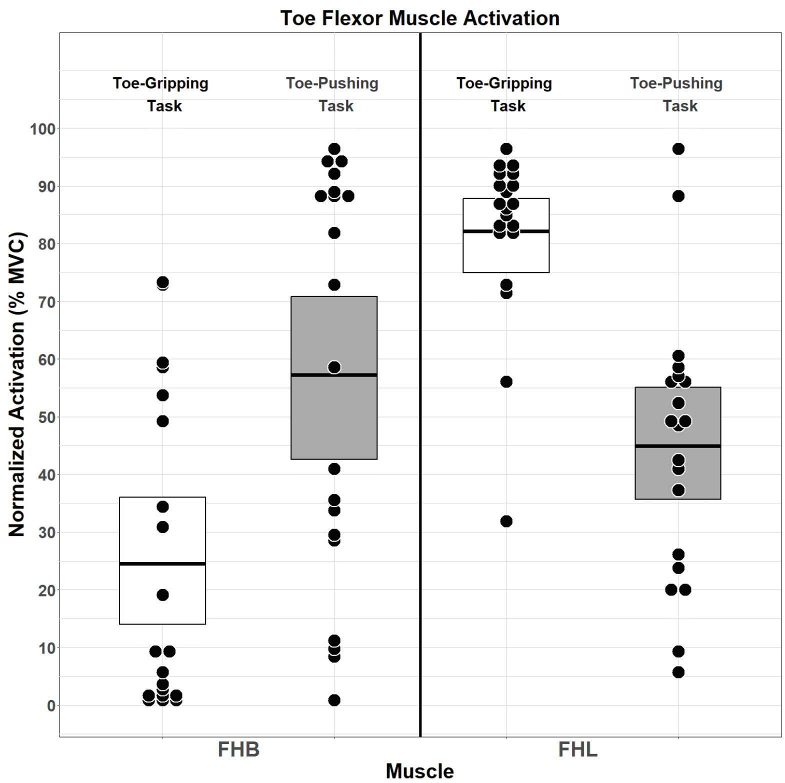

Fig. 4. Crossbar plots depicting the mean and 95% confidence interval for flexor hallucis brevis (FHB) and flexor hallucis longus (FHL) activation during each dynamometer task

Table 1. Descriptive statistics [Mean (SD)] for force and muscle activation outcome measures along with two-way mixed intra-class correlation (ICC) coefficients for absolute agreement

Force exerted				Muscle	Activation magnitude	
Raw [kg]		Normalized [% Body Mass]			[% MVC]	
Toe-gripping	Toe-pushing	Toe-gripping	Toe-pushing		Toe-gripping	Toe-pushing
12.6(4.8) ICC = 0.91	11.0 (5.1) ICC = 0.85	18.6 (5.9) ICC = 0.86	16.0 (7.7) ICC = 0.93	FHB	24.5 (26.9) ICC = 0.95	57.2 (34.8) ICC = 0.92
				FHL	82.2 (15.1) ICC = 0.73	44.9 (23.4) ICC = 0.89

<10% MVC. This observation does not directly support our hypothesis, which stated that both muscles would activate during gripping activity. In contrast, muscle activation during the toe-pushing task in MTP dorsiflexion appeared more reliant on the FHB for most participants, supporting our hypothesis for this task.

It is likely that the length of these muscles and their respective positions on the length-tension relationship influenced their recruitment during these two tasks. In both tasks, the ankle joint was in a neutral position. In the toe-gripping task, the MTP and IP joints were allowed to plantar flex. This would shorten both the FHB and FHL, but as a percentage of resting length it would likely shorten the FHB more. This could help explain the increase in reliance on FHL in the toe-gripping task. In the toe-pushing task, the FHL and FHB would both be lengthened as a result of MTP dorsiflexion. Again, as a percent of resting length, it is likely that the FHB lengthened more. Goldmann and Brüggemann reported that plantar flexing the ankle while dorsiflexing the toes, which is the posture adopted in late stance phase of gait, helped to avoid a disadvantage in the force-length relationship of the toe flexor muscles and maintain torque production ability [2]. Combined with the finding that the FHB had greater activation during the toe-pushing task compared to the FHL, this could indicate that the increase in force production measured by Goldmann and Brüggemann was driven primarily by increased contribution from the FHB. This interpretation is supported by findings presented by Farris et al. [1] who showed that a tibial nerve block at the ankle, which impairs FHB but not FHL, resulted in decreased MTP joint torsional stiffness in the late stance phase of gait.

There are important functional implications for an increased understanding of extrinsic and intrinsic foot muscle contributions to toe functions. MTP dorsiflexion in the late stance phase is an important functional requirement of propulsion during gait. For sprinters, this MTP extension may form the basis of elite performance [10]. The findings of the current study suggest that the FHB and perhaps intrinsic foot muscles more broadly, are important targets to improve MTP joint torsional stiffness and MTP plantar flexion torque in the toes in these functional positions of MTP dorsiflexion. Considering the other task in this study (with MTP and IP joints plantar flexed), these findings suggest the FHL could be a target of improving function during tasks with a neutral or plantar flexed hallux. This challenges current rehabilitation exercises used by physical therapists to focus on intrinsic foot muscles such as the towel curl. This exercise involves plantar flexing the MTP and IP against a towel lying on the ground. Data from the current study suggests this exercise primarily activates the FHL and will fail to activate the FHB entirely in about half of participants. This could explain why some studies have reported better clinical outcomes with a "short foot exercise" compared to a towel curl exercise [11]. Furthermore, recent studies have begun to utilize the towel curl exercise to specifically target extrinsic foot muscles, [9]. The findings of the current study would support this latter use of the towel curl exercise.

It is important to note that there was quite a bit of individual variation in how participants coordinated these muscles during these two isometric toe flexion tasks. In the toe-gripping task, half of participants activated FHB <10% of MVC but half activated between 20 and 75% of MVC. A subsequent analysis did not reveal any obvious differences between these two groups of individuals. For instance, those who activated the FHB during the toe-gripping task did not produce more force than those who did not (FHB <10% of MVC produced on average a normalized force of 18.1% body mass and FHB >10% of MVC produced on average a normalized force of 19.0% body mass).

There are a few possible explanations for the variation in muscle coordination. Joint range of motion was limited due to the arrangement of the foot on the dynamometer, but it is possible that some individuals plantar flexed the MTP or IP joints more than others during the toe-gripping task. The joint angles in the toe-pushing tasks were more strictly controlled given the structure of the dynamometer. There could also be differences in resting abduction/adduction position of the toes or in arch height or foot posture index between individuals, which could affect muscle lengths and moment arms, and therefore force production at the toes. These measures were not captured in this study. We also know that there are anatomical variations in tendonous connections between the toes, which might have some influence on intrinsic and extrinsic foot muscle coordination [16].

There were important limitations to mention in the current study. First, only two hallux flexors were compared in the present study – FHB and FHL. There are other intrinsic foot muscles that contribute to hallux plantar flexion including the abductor and adductor hallucis muscles. In fact, Kusagawa et al. [8] reported that the adductor muscle size exhibited the strongest correlation with toe flexor strength in a toe-gripping task. It is also important to note that in both tasks, the lesser toes were in contact with the dynamometer. These toes may have influenced the toe flexor force production measured. We do know, however, that the hallux is much stronger than the lesser toes, so this was still likely the primary contributor to the outcomes measured [13]. Finally, our study on healthy, young adults has limited generalizability to patient populations. In these populations, we know that toe deformities such as hallux rigidus or hallux valgus alter joint mobility, plane of motion and direction of muscle pull. Future work should assess toe flexor strength and activation patterns in these populations.

5. Conclusions

Despite consistent force production in toe-gripping and toe-pushing tasks, participants utilized the FHL and FHB completely differently. In the toe-gripping task with MTP and IP plantar flexion allowed, the FHL was activated to a much greater extent than the FHB. In contrast, muscle activation during the toe-pushing task in MTP dorsiflexion appeared more reliant on the FHB for most participants. These different contributions from the FHL and FHB to toe flexor force production in these two tasks are potentially driven by differences in muscle functional length among other factors. These findings help to inform the selection of rehabilitation and training exercises meant to preferentially target intrinsic or extrinsic foot musculature.

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Conflict of interest statement

The authors have no conflicts of interest to report.

Data sharing statement

The data that support the findings of this study are openly available in Open Science Framework at osf.io/7pzva.

Author contributions

Study was prepared by KMR, TK, and KK. TK obtained financial support for the study. Research was executed by KMR and TK. Data were analyzed and interpreted by KMR, DOW, and KK. KMR and DOW led preparation of the manuscript with revision and approval by all authors.

References

[1] 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, https://doi.org/10.1073/pnas.1812820116

[2] Goldmann J.P., Brüggemann G.P., *The potential of human toe flexor muscles to produce force*, J. Anat., 2012, 221 (2), 187–194, https://doi.org/10.1111/j.1469-7580.2012.01524.x

[3] Hakim-Zargar M., Aronow M.S., Gibson L., Obopilwe E., *Implications for the anatomy of the flexor hallucis brevis insertion*, Foot Ankle Int., 2010, 31 (1), 65–68, https://doi.org/10.3113/FAI.2010.0065

[4] Kelly L.A., Cresswell A.G., Racinais S., Whiteley R., Lichtwark G., *Intrinsic foot muscles have the capacity to control deformation of the longitudinal arch*, J. R. Soc. Interface, 2014, 11, 20131188, https://doi.org/10.1098/rsif.2013.1188

[5] Kurihara T., Rowley M., Reischl S., Baker L., Kulig K., *Effect of a task's postural demands on medial longitudinal arch deformation and activation of foot intrinsic and extrinsic musculature*, Acta Bioeng. Biomech., 2020, 22 (4), 1–15, https://doi.org/10.37190/ABB-01623-2020-02

[6] 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, https://doi.org/10.1371/journal.pone.0262100
[7] 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, 26–31, https://doi.org/10.1186/1757-1146-7-26
[8] 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, https://doi.org/10.1186/s13047-022-00532-9
[9] LAI Z., PANG H., HU X., DONG K., WANG L., *Effects of intrinsic-foot-muscle exercise combined with the lower extremity resistance training on postural stability in older adults with fall risk: study protocol for a randomised controlled trial*, Trials, 2021, 22 (1), 587, https://doi.org/10.1186/s13063-021-05554-5
[10] LEE S.S.M., PIAZZA S.J., *Built for speed: musculoskeletal structure and sprinting ability*, J. Exp. Biol., 2009, 212 (Pt 22), 3700–3707, https://doi.org/10.1242/jeb.031096
[11] LYNN S.K., PADILLA R.A., TSANG K.K.W., *Differences in static- and dynamic-balance task performance after 4 weeks of intrinsic-foot-muscle training: the short-foot exercise versus the towel-curl exercise*, J. Sport Rehabil., 2012, 21 (4), 327–333, https://doi.org/10.1123/jsr.21.4.327
[12] DE MAESENEER M., MOYSON N., LENCHIK L., CATTRYSSE E., SCAFOGLIERI A., ROOSE R., SHAHABPOUR M., *MR imaging-anatomical correlation of the metatarsophalangeal joint of the hallux: Ligaments, tendons, and muscles*, Eur. J. Radiol., 2018, 106, 14–19, https://doi.org/10.1016/j.ejrad.2018.07.003
[13] 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, https://doi.org/10.2519/jospt.2016.6597
[14] PÉREZ 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 Biomechanics, 2022, 130, 110863. https://doi.org/10.1016/j.jbiomech.2021.110863
[15] PEROTTO A.O., DELAGI E.F., IAZZETTI J., MORRISON D., *Anatomical Guide for the Electromyographer*, 5th ed., Charles C Thomas Publisher, 2011.
[16] PRETTERKLIEBER B., *The high variability of the chiasma plantare and the long flexor tendons: Anatomical aspects of tendon transfer in foot surgery*, Ann. Anat., 2017, 211, 21–32, https://doi.org/10.1016/j.aanat.2017.01.011
[17] RIDGE S.T., ROWLEY K.M., KURIHARA T., MCCLUNG M., TANG J., REISCHL S., KULIG K., *Contributions of Intrinsic and Extrinsic Foot Muscles during Functional Standing Postures*, Biomed Res. Int., 2022, 7708077, https://doi.org/10.1155/2022/7708077
[18] 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 (Basel)., 2021, 10 (1), 48, https://doi.org/10.3390/biology10010048
[19] SOYSA A., HILLER C., REFSHAUGE K., BURNS J., *Importance and challenges of measuring intrinsic foot muscle strength*, J. Foot Ankle Res., 2012, 5, 29–42, https://doi.org/10.1186/1757-1146-5-29
[20] YUASA Y., KURIHARA T., ISAKA T., *Relationship Between Toe Muscular Strength and the Ability to Change Direction in Athletes*, J. Hum. Kinet., 2018, 64, 47–55, https://doi.org/10.1515/hukin-2017-0183

Supplementary material

Normalization of electromyography signals

Due to the wide variety of MMT tasks that participants performed during the data acquisition, we chose to normalize the muscle activations during the dynamometry tasks to three different values. The first value corresponded to the maximum activation during either of the TFS dynamometer task trials (hereafter referred to as TFS-MVC) while the second is the maximum activation during any of the four MMTs or the two TFS tasks (hereafter referred to as MMT-MVC). Upon inspecting the maximum values used in the MMT-MVC normalization, we discovered that some of these values corresponded to foot or toe movements that were not typical of those seen during the dynamometer task performance. For instance, it was logical that participants might maximally activate the FHB during the ankle plantarflexion MMT since this motion involves bringing the foot and toes downward. However, some of the MMT-MVC normalization values corresponded to MMT tasks that did not have such a logical connection and could have been related to aberrant activation peaks. The third normalization method we tested therefore used the maximum activation during any MMT or TFS task that had some functional expectation of activation of the muscle (hereafter referred to as Functional-MVC). Note that in the group averages, there was very little difference between using the MMT-MVC and using the Functional-MVC. Here in this Supplemental, we report data normalized using all methods for transparency.

In the manuscript, we chose to report data normalized to Functional-MVC only. The following MMT tasks were used in this normalization procedure: when normalizing activation measures from the flexor hallucis longus (FHL), all but one subject produced their maximum FHL activation during the toe flexor strength (dynamometer) tasks. The remaining subject produced maximum FHL activation during the resisted toe abduction MMT. When normalizing activation measures from the flexor hallucis brevis (FHB), 8 subjects produced maximum FHB activation during the toe flexor strength tasks, 10 subjects produced maximum FHB activation during a resisted toe abduction MMT, and

Supplementary material – Table 1. Descriptive statistics [Mean (SD)] for force and muscle activation outcome measures

Muscle	Force exerted				Activation magnitude [%]					
	Raw [kg]		Normalized [% Body Mass]		TFS-MVC		MMT-MVC		Functional-MVC	
	Toe-gripping	Toe-pushing	Toe-gripping	Toe-pushing	Toe-gripping	Toe-pushing	Toe-gripping	Toe-pushing	Toe-gripping	Toe-pushing
FHB	12.6 (4.8)	11.0 (5.1)	18.6 (5.9)	16.0 (7.7)	35.7 (31.4)	78.3 (20.3)	22.3 (25.0)	50.4 (35.2)	24.5 (26.9)	57.2 (34.8)
FHL					84.1 (9.9)	47.1 (24.7)	81.2 (16.2)	44.5 (23.8)	82.2 (15.1)	44.9 (23.4)

2 subjects produced maximum FHB activation during a resisted foot inversion MMT. This comparison suggests that subjects had more difficultly maximally activating FHB, an intrinsic foot muscle, compared to the FHL, an extrinsic foot muscle, as a greater variety of MMTs were required to elicit maximal FHB activation among these 20 participants. This mirrors what has been reported previously about the difficulty of maximally activating intrinsic foot muscles [14].