*Article*

AMERICAN ORTHOPAEDIC FOOT & ANKLE SOCIETY

Foot & Ankle Orthopaedics
2024, Vol. 9(3) 1–8

DOI: 10.1177/24730114241266847
journals.sagepub.com/home/fao

# Relationship Between the Flexion Torque of the First Metatarsophalangeal Joint and Intrinsic Foot Muscles Depends on the Ankle Joint Position

**Ryo Otani, MS[1], Hideo Nishikawa, MD[1], Junya Saeki, PhD[2], and Masatoshi Nakamura, PhD[3]**

**Abstract**

**Background:** Clinicians and researchers are beginning to pay attention to the importance of the intrinsic foot muscles (IFMs). Among IFMs, the abductor hallucis (AbH) is associated with foot disorders. However, so far no method for assessing the strength of the AbH has been established. In addition, previous studies have shown increased IFM activity in the plantarflexed position of the ankle. Therefore, this study tests the hypothesis that a correlation will be found between the cross-sectional area (CSA) of the AbH and the flexion torque and that the first metatarsophalangeal (MTP) joint would be stronger in the plantarflexed (PF) position of the ankle joint than in the neutral (N) position.

**Methods:** Eight male and 8 female patients (16 lower limbs) were included in this study to measure the CSA of IFM and the extrinsic foot muscles of the lower leg. Furthermore, the flexion torque of the first MTP joint was measured using a handheld dynamometer at the N and PF positions of the ankle joint. Correlation analysis was performed to examine the relationship between the CSA of each muscle and the flexion torque of the first MTP joint in the N and PF positions.

**Results:** In the N position, a correlation was found between the flexion torque of the first MTP joint and the CSA of the AbH ($r = 0.818$), flexor hallucis brevis ($r = 0.730$), and flexor hallucis longus ($r = 0.726$). In the PF position, a correlation was found between the flexion torque of the first MTP joint and the CSA of the AbH ($r = 0.863$) and flexor hallucis brevis ($r = 0.680$). ($P < .05$)

**Conclusion:** Overall, this study suggested that by measuring flexion torque of the first MTP joint in the PF position, AbH strength can be estimated without using any expensive equipment.

**Level of Evidence:** Level V, mechanism-baced reasoning.

**Keywords:** intrinsic foot muscle, abductor hallucis, handheld dynamometer, cross-sectional area, ultrasound

## Introduction

Previous studies have revealed that the foot and ankle joint is a highly complex structure with various roles in gait and postural control, such as stability, mobility, weightbearing, and elastic energy release.[3,6,16] These functions of the foot and ankle joint are regulated by the extrinsic foot muscles and the intrinsic foot muscles (IFM), the importance of which has been reported.[23] While walking, the IFM works with the extrinsic foot muscles.[32] Thus, many clinicians and

[1]Nishikawa Orthopedic Clinic, Ogi, Saga, Japan
[2]Department of Physical Therapy, Osaka Kawasaki Rehabilitation University, Kaizuka City, Osaka Prefecture, Japan
[3]Faculty of Rehabilitation Sciences, Nishi Kyushu University, Kanzaki, Saga, Japan

**Corresponding Author:**
Ryo Otani, MS, Department of Rehabilitation Medicine, Nishikawa Orthopedic Clinic, 2171-5 Mikatsukicho-chokanda, Ogi, Saga 845-0021, Japan.
Email: otani.mail@gmail.com

researchers have been paying attention to the importance of the IFM in addition to the extrinsic foot muscles.

The clinically important muscle in IFM is the abductor hallucis (AbH). AbH is the muscle with the largest cross-sectional area (CSA) and volume in IFM.[21,30] A previous study showed that AbH activity decreased in patients with hallux valgus.[2] In addition, patients with flatfoot and hallux valgus have a smaller CSA of the AbH.[1,29] It has also been reported that runners with injuries such as medial tibial stress syndrome, patellofemoral pain, and plantar fasciitis have smaller CSA in AbH.[33] Because AbH is associated with various diseases, examining how to assess CSA in AbH can be valuable to clinical practice, particularly in prevention and rehabilitation.

Plantarflexion of the first metatarsophalangeal (MTP) joint is one of the AbH functions,[28] and Olivera et al[24] have shown that electrical stimulation of the AbH to induce contraction produces flexion torque at the first MTP joint. Therefore, previous studies analyzed various methods of evaluating the AbH function using flexion of the big toe.[5,9,11] However, these results are subjective to the inspector and cannot be objectively quantified. To solve these problems, previous studies have measured toe flexion and pressure forces with a strain gauge, dynamometer, and pedobarography.[19,20,22,26] These studies have revealed a significant correlation with CSA for some IFMs. Among them, Latey et al[22] reported a correlation between the great toe pressure measured by pedobarography in the standing position and CSA of the AbH. However, because only AbH and flexor hallucis brevis were measured in their study, they were not considered in relation to other muscles. Therefore, it is necessary to consider clinical evaluation methods that better represent the function of AbH.

Thus, we sought to determine the effect of ankle joint position on IFM. Hashimoto and Sakuraba reported that the IFM muscle activity during toe flexion was greater in maximum plantarflexion of the ankle joint compared with the ankle joint at neutral (N) position.[15] This result suggests that a plantarflexed (PF) position may increase the IFM activity. Therefore, the flexion torque of the first MTP joint in the ankle at the PF position may reflect the strength of the AbH muscles among IFMs. However, previous studies that measured the muscle strength in IFM performed toe exercises only in the ankle at the N position. Thus, the relationship between the toe muscle strength in the ankle at the PF position and CSA of AbH is unclear.

To address this question, we aimed to test the hypothesis that the correlation between the CSA of AbH and flexion torque of the first MTP joint would be stronger in PF than in the N position. The extrinsic foot muscles with ankle plantarflexion action shorten in the PF position,[25] and isometric contractility is reduced as muscle fibers shorten from their optimum length.[12] Furthermore, given that IFM increases muscle activity in the PF position,[15] our hypothesis is expected to be correct.

In this study, we investigated the relationship between the flexion torque of the first MTP joint and the CSA of the muscles of the lower extremity in the N and PF positions of the ankle joint. By investigating the relationship between the 2 positions, it is possible to examine which muscles determine the toe strength in the PF position of the ankle joint. Based on the study results, we would like to help establish an evaluation method for the AbH that can be easily implemented in clinical practice.

## Materials and Methods

### Study Design

This study is a cross-sectional study.

### Setting

This study was conducted at the medical institution to which the author belongs from February to March 2023.

### Sample Size

Sample sizes were calculated using Statistical Packages of Social Sciences (SPSS version 28.0; IBM Corp, Armonk, NY). We are planning a study to determine Pearson correlation coefficient between the 2 variables (CSA, the flexion torque of the first MTP joint). The correlation coefficient reported in the previous study was $r = 0.645$.[22] To reject the null hypothesis that the correlation coefficient is $r = 0$ with a power of 0.8, a sample of 14 persons is needed. The Type I error probability associated with this null hypothesis test is 0.05.

### Participants

This study was conducted in compliance with the Declaration of Helsinki and received approval from the ethics committee of the authors' affiliated institution. The eligibility criteria for participants were that they were aged $\geq$18 years and did not have a neuromuscular disease of the lower limbs that was currently being treated. The exclusion criteria were a history of neuromuscular disease of the lower limbs in the past year. We explained the outline of the research to staff members of the author's organization who met the eligibility criterion. We asked staff who expressed an interest to participate in the research. The participants consisted of 8 males and 8 females, aged 18-35 years (age, $26.5 \pm 5.7$; height, $164.9 \pm 11.8$ cm; weight, $58.7 \pm 12.4$ kg, mean $\pm$ SD). A total of 16 lower extremities (dominant leg) were included in the study. The principal investigator provided an explanation of the study to the participants. Then, written informed consent was obtained from all patients.

### CSA Measurement

Measurement was performed using a digital ultrasonic diagnostic device (Noblus, Hitachi, Ltd, Tokyo, Japan) equipped with a linear probe ranging from 5 to 18 MHz. Following the protocol from a previous study,[8] ultrasonography was used to measure the CSA of IFM and the extrinsic foot muscles of the lower leg, and specific measurement sites can be found in Figure 1. Participants underwent AbH, flexor digitorum brevis (FDB), and flexor hallucis brevis (FHB) measurements in the extended position of the knee joint and the N position of the ankle joint. Additionally, the flexor digitorum longus (FDL), flexor hallucis longus (FHL), and peroneus longus and brevis (PER) were measured in the flexed position of the knee joint and the N position of the ankle joint (at 0 degrees). The measurements were performed by a physical therapist with 13 years of clinical experience. The target muscles were contracted in this study to confirm the muscle outlines. The experimenter saved videos (AMI files) of muscle contraction. The joint motions for each muscle were as follows: AbH, FHB, and FHL on flexion of the big toe; FDB and FDL on flexion of the first to fifth toes; and PER on ankle joint eversion. After checking the outline of the muscle, CSA was measured using images at rest.

### Image Measurements

The video files were analyzed using the Image J software (National Institute for Health, Bethesda, MD). The CSA measurement was performed by the same evaluator who conducted ultrasonographic measurements. Previous studies have demonstrated high interrater reliability (intraclass correlation coefficient [ICC] 3.1, range 0.91-0.98) regarding CSA measurements using this method.[8] To obtain the ICC in this experiment, the same evaluator performed 2 CSA measurements on the same day for 5 participants before this experiment.

### Big Toe Strength

The flexion torque of the first MTP joint was measured using a handheld dynamometer (HHD) (mobieZ; SAKAI Medical Co, Ltd, Tokyo, Japan). Participants were placed in a sitting position with the knee joint on the measurement side in full extension. A treatment bed (IP-WPH003; Inter Reha Co, Ltd, Tokyo, Japan) was used to fix the participant's ankle joint in the N (ankle joint 0 degrees) and PF (ankle joint plantarflexion 45 degrees) positions. Participants practiced flexion movement of the first MTP at their respective ankle angles, followed by performing 3 consecutive maximal isometric contractions of 3 seconds. The subject performed the force against the resistance of the first MTP joint in the dorsiflexion direction without any joint movement. The peak force of each contraction was recorded by HHD, and the average value was calculated. An experienced physiotherapist (with 13 years of clinical experience) performed the measurements. The evaluator immobilized the participants' foot and HHD, ensuring that they did not perform plantarflexion of the ankle and flexion movements of the hallux IP joint (see Figure 2). Additionally, the length of the hallux (distance beyond the MTP joint) was measured, and the flexion torque of the first MTP joint was calculated based on the average value of the obtained force using the HHD.

### Date Collection

All measurements were taken on the same day. To prevent the effects of temporary muscle hypertrophy caused by muscle contraction, the measurements were carried out in the following order: (1) CSA using ultrasonography and (2) the flexion torque of the first MTP joint.

### Statistical Analysis

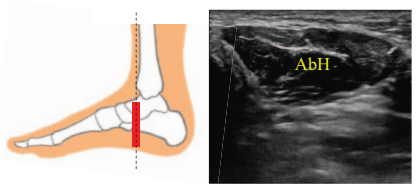
Statistical analysis was conducted using SPSS (version 28.0; IBM Corp). Preliminary measurements were used to obtain the ICC (1, 2) of CSA measurements. Furthermore, ICC (1, 3) was calculated from the results of the flexion torque of the first MTP joint measurement. Pearson correlation coefficient was calculated using the CSA of each muscle as the independent variable and the flexion torque of the first MTP joint as the dependent variable for each position. To control the overall Type I error, the $P$ value was adjusted using Bonferroni correction. After the correction, the significance level was set at $P < .05$.

## Results

ICC (1, 2) obtained from preliminary CSA measurements were AbH of 0.974, FDB of 0.908, FHB of 0.921, FDL of 0.877, FHL of 0.984, and PER of 0.972, confirming high intraclass reliability. The ICC (1.3) obtained from the first MTP flexion torque measurement was 0.968 for the N position and 0.973 for the PF position, confirming high intraclass reliability. The measured values of flexion torque of the first MTP joint and the CSA for each muscle are presented in Table 1. In addition, the scatter plots for both are shown in Figure 3. The correlation coefficients between the flexion torque of the first MTP joint and the CSA of each muscle are shown in Table 2. In the N position, a correlation was found between the flexion torque of the first MTP joint and the CSA of the AbH, FHB, and FHL. In the PF position, a correlation was found between the flexion torque of the first MTP joint and the CSA of the AbH and FHB.

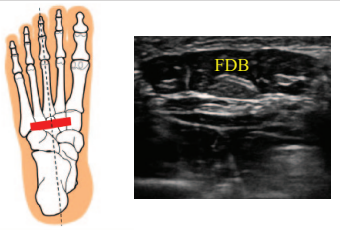
AbH : Abductor Hallucis

The CSA was acquired on a scanning line drawn perpendicular to the long axis of the foot at the anterior aspect of the medial malleolus.



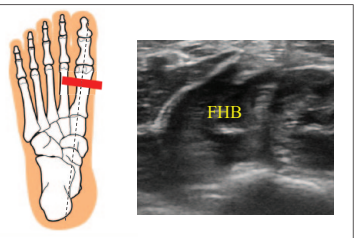

FDB : Flexor Digitorrum Brevis

longitudinally along a line from the medial tubercle of the calcaneus to the third toe at the thickest portion of the muscle and then the probe was then rotated through 90° to measure the CSA.



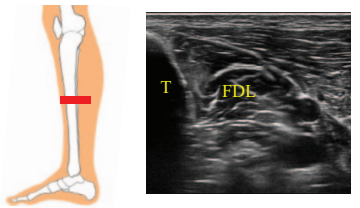

FHB : Flexor Hallucis Brevis

longitudinally along the shaft of the 1st metatarsal at the thickest portion of the muscle, and then the probe was rotated 90° to obtain CSA of the muscle.




FDL : Flexor Digitorum Longus

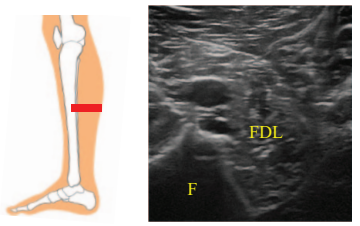
transverse line drawn at 50% of the distance between the medial tibial plateau and inferior border of the medial malleolus on the medio-posterior aspect of the tibia.
T : Tibia




FHL : Flexor Hallucis Longus

Probe at same level and posteriorly to FDL

F : Fibula




PER : Peroneus longus and brevis

captured at a line 50% between fibular head and the inferior border of the lateral malleolus.
F : Fibula

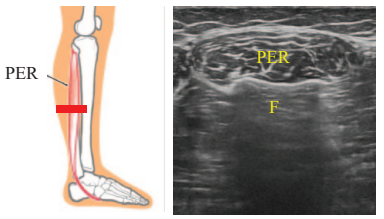



**Figure 1.** Cross-sectional area measurement methods (probe position, orientation, and sample images).

**Figure 2.** The flexion torque of the first metatarsophalangeal joint was measured using a handheld dynamometer in the N (ankle joint 0 degrees) and PF (ankle joint plantarflexion 45 degrees) positions. N, neutral; PF, plantarflexed.

**Table 1.** Results for CSA of Lower Limb Muscles and First MTP Torque.

| Variable | Value, Mean ± SD |
|---|---|
| CSA, $cm^2$ | |
| AbH | 2.36 ± 0.54 |
| FDB | 1.67 ± 0.44 |
| FHB | 1.55 ± 0.48 |
| FDL | 1.83 ± 0.56 |
| FHL | 2.34 ± 0.64 |
| PER | 3.64 ± 0.63 |
| First MTP torque, Nm | |
| N position | 2.10 ± 0.84 |
| PF position | 1.41 ± 0.68 |

Abbreviations: AbH, abductor hallucis; CSA, cross-sectional area; FDB, flexor digitorum brevis; FDL, flexor digitorum longus; FHB, flexor hallucis brevis; FHL, flexor hallucis longus; MTP, metatarsophalangeal; N, neutral; PER, peroneus longus and brevis; PF, plantarflexed.

## Discussion

The aim of this study is to test the hypothesis that the PF position has a stronger correlation between the CSA of the AbH and the flexion torque of the first MTP joint than the N position. Based on our literature search, this is the first study to examine the relationship between the flexion torque of the first MTP joint and the CSA of the extrinsic and intrinsic foot muscles in both N and PF positions.

FHL has the action of flexing the great toe in the N position.[13,19] On the other hand, FHL shortens in the PF position because of its ankle plantarflexion action,[25] and isometric contractility is reduced as muscle fibers shorten from their optimal length.[12] Furthermore, Hashimoto and Sakuraba reported that the action potential of the IFM during toe flexion is higher in the PF position than in the N position.[15] Therefore, it is considered that the contribution of AbH and FHB increased relatively because FHL does not have much effect on the flexion of the first MTP joint at the PF position.

According to Guilford's Rule of Thumb, a method of interpreting correlation coefficients,[14] AbH showed high correlation in both the N position ($r=0.818$) and the PF position ($r=0.863$). On the other hand, FHB showed high correlation at the N position ($r=0.730$) but moderate correlation at the PF position ($r=0.680$). Previous research has investigated the relationship between CSA of IFM and flexion force of the big toe, and correlations have been found only for AbH.[22] The results of this study show a similar trend, suggesting that the flexion torque of the first MTP

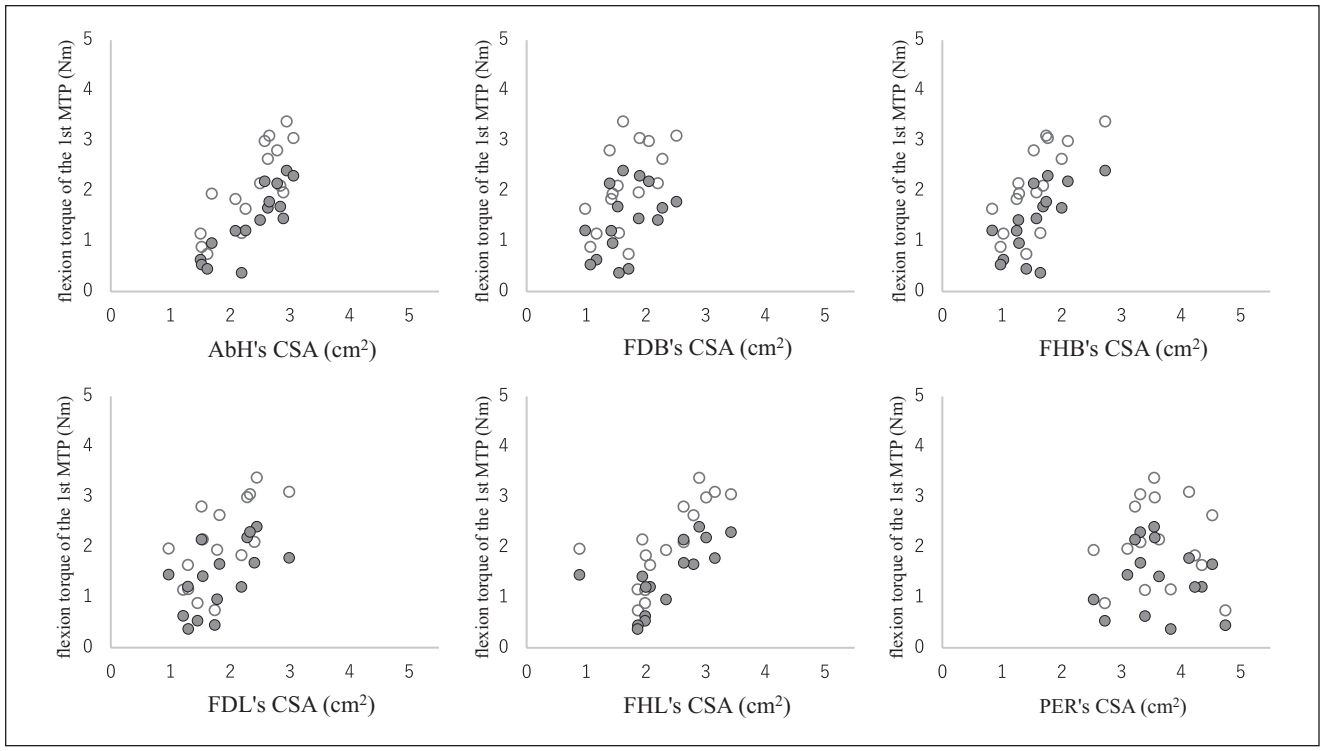



**Figure 3.** The relationship between CSA of each muscle and first MTP flexion torque. N=16, open circle: N position. filled circle: PF position.

**Table 2.** Pearson Correlation Coefficient Between Torque and CSA of the Individual Muscles.[a]

| | N-Position Torque | | PF-Position Torque | |
|---|---|---|---|---|
| CSA | *R* | *P* | *r* | *P* |
| AbH | **0.818*** | **.001** | **0.863*** | **>.001** |
| FDB | 0.565 | .270 | 0.440 | >.999 |
| FHB | **0.730*** | **.016** | **0.680*** | **.045** |
| FDL | 0.645 | .084 | 0.572 | .246 |
| FHL | **0.726*** | **.017** | 0.670 | .0548 |
| PER | −0.049 | >.999 | −0.075 | >.999 |

Abbreviations: AbH, abductor hallucis; CSA, cross-sectional area; FDB, flexor digitorum brevis; FDL, flexor digitorum longus; FHB, flexor hallucis brevis; FHL, flexor hallucis longus; MTP, metatarsophalangeal; N, neutral; PER, peroneus longus and brevis; PF, plantarflexed.
*Boldface indicates significance ($P < .05$).
[a]*P* values were adjusted by Bonferroni correction.

joint in the PF position is more affected by AbH than FHB. AbH is a multipennate muscle with an advantage in generating force.[30] It has the largest PCSA of the IFMs, providing greater tension than FHB.[18] Consequently, the influence of FHB on the flexion torque of the first MTP joint is smaller than that of AbH.

We consider the clinical applications of this study. The joint torque exerted by muscle contraction is strongly associated with CSA.[7] Therefore, the flexion torque of the first MTP joint in the PF position may reflect the CSA of the AbH and FHB, and it especially strongly reflects AbH. As the flexion torque of the first MTP joint in the PF position correlates with the CSA of the AbH, so it may be possible to estimate the strength of the AbH without expensive equipment, such as ultrasonic diagnostic devices or magnetic resonance imaging. Currently reported clinical testing methods for IFM, such as manual muscle testing (MMT), are performed with toe MTP joint flexion in the N position.[5] However, based on our study, measuring the muscle strength in the N position does not seem to provide a focused evaluation of AbH. In contrast, measuring the flexion torque of the first MTP joint in the PF position may allow for a focused evaluation of AbH. In foot disorders related to AbH, measuring the first MTP flexion torque in the PF position may allow for the early detection of muscle weakness and/or atrophy in AbH. When found, clinicians may consider using exercises that flex the first metatarsophalangeal joint in the PF position as a training method for AbH. The toe curl exercises and short foot exercises, which are representative training methods for IFM including AbH, are exercises performed in the N position of the ankle joint.[17] Compared with these exercises, the first MTP flexion in the PF position of the ankle joint may have the potential to greatly improve the CSA and strength of the AbH.

There were some limitations in this study. First, the foot was manually immobilized during the measurement of the

flexion torque of the first MTP joint. However, the flexion torque of the first MTP joint measured in this study is much smaller than that of the knee and ankle joints; thus, manual fixation is considered to have a small negative effect. Second, muscles with flexion action at the first MTP joint include the adductor hallucis oblique head (ADDH-OH).[13] However, when measuring the CSA of ADDH-OH using ultrasonography, the boundary with the surrounding tissues is unclear[27] and could not be measured in this study. Third, this study used the anatomical cross-sectional area (ACSA) as the measured parameter in ultrasonography, not the physiological cross-sectional area (PCSA). The PCSA, which is calculated based on muscle volume, pennation angle, and fascicle length, is strongly correlated with the torque generated by the muscles.[10] Therefore, it is preferable to employ PCSA rather than ACSA to examine the relationship between muscle size and toe strength. However, a previous study showed that ACSA can reflect muscle strength with comparable accuracy to PCSA.[4] Therefore, the ACSA in this study may adequately reflect the muscle strength of the IFM and lower-leg muscles. Fourth, this study did not have sufficient power to prevent type 2 errors due to multiple comparison. Therefore, the effects of muscle groups that were not shown to be significantly correlated in this study cannot be excluded. We would like to verify the results of this study by increasing the sample size and improving detection power in the future. Fifth, this study did not compare muscle strength in the neutral and plantarflexion positions of the ankle joint. Measurements of the CSA can be done in those 2 positions in future studies. Furthermore, as the study participants were healthy adults, data do not include younger or older participants. However, the relationship between the CSA and muscle strength is independent of age,[31] suggesting that similar results are expected in younger and older individuals. Finally, there are concerns that this study has been unable to rule out the effects of a history of neuromuscular diseases of the lower limbs and that it cannot be generalized to subjects with foot diseases or deformities. Future studies should confirm whether the relationship between IFM and the flexion torque of the first MTP joint is also observed in these patients.

In this study, the flexion torque of the first MTP joint was measured in different ankle joint positions, and the correlation between the CSA of the muscles involved in the foot was investigated. The results of this study revealed that the flexion torque of the first MTP joint measured in the PF position was more strongly associated with the CSA of the AbH than the N position.

## Ethical Approval

Ethical approval for this study was obtained from Ethics Committee of the Nishikawa Orthopedic Clinic.

## Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. Disclosure forms for all authors are available online.

## Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

## ORCID iD

Ryo Otani, MS, https://orcid.org/0009-0004-9794-1911

## References

1. Angin S, Crofts G, Mickle KJ, Nester CJ. Ultrasound evaluation of foot muscles and plantar fascia in pes planus. *Gait Posture*. 2014;40(1):48-52. doi:10.1016/j.gaitpost.2014.02.008
2. Arinci Incel N, Genç H, Erdem HR, Yorgancioglu ZR. Muscle imbalance in hallux valgus: an electromyographic study. *Am J Phys Med Rehabil*. 2003;82(5):345-349. doi:10.1097/01.PHM.0000064718.24109.26
3. Asghar A, Naaz S. The transverse arch in the human feet: a narrative review of its evolution, anatomy, biomechanics and clinical implications. *Morphologie*. 2022;106(355):225-234. doi:10.1016/j.morpho.2021.07.005
4. Bamman MM, Newcomer BR, Larson-Meyer DE, Weinsier RL, Hunter GR. Evaluation of the strength-size relationship in vivo using various muscle size indices. *Med Sci Sports Exerc*. 2000;32(7):1307-1313. doi:10.1097/00005768-200007000-00019
5. Brown M, Avers D, eds. Hallux MP flexion. In: *Daniels and Worthingham's Muscle Testing*. 10th ed. Saunders; 2018:293.
6. Castro MD. Ankle biomechanics. *Foot Ankle Clin*. 2002;7(4):679-693. doi:10.1016/S1083-7515(02)00049-9
7. Castro MJ, McCann DJ, Shaffrath JD, Adams WC. Peak torque per unit cross-sectional area differs between strength-trained and untrained young adults. *Med Sci Sports Exerc*. 1995;27(3):397-403.
8. Crofts G, Angin S, Mickle KJ, Hill S, Nester CJ. Reliability of ultrasound for measurement of selected foot structures. *Gait Posture*. 2014;39(1):35-39. doi:10.1016/j.gaitpost.2013.05.022
9. de Win MML, Theuvenet WJ, Roche PW, de Bie RA, van Mameren H. The paper grip test for screening on intrinsic muscle paralysis in the foot of leprosy patients. *Int J Lepr Other Mycobact Dis*. 2002;70(1):16-24.
10. Fukunaga T, Miyatani M, Tachi M, Kouzaki M, Kawakami Y, Kanehisa H. Muscle volume is a major determinant of joint torque in humans: muscle volume and joint torque. *Acta Physiol Scand*. 2001;172(4):249-255. doi:10.1046/j.1365-201x.2001.00867.x
11. Garth WP, Miller ST. Evaluation of claw toe deformity, weakness of the foot intrinsics, and posteromedial shin pain. *Am J Sports Med*. 1989;17(6):821-827. doi:10.1177/036354658901700617

12. Gordon AM, Huxley AF, Julian FJ. The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *J Physiol*. 1966;184(1):170-192. doi:10.1113/jphysiol.1966.sp007909
13. Green SM, Briggs PJ. Flexion strength of the toes in the normal foot. An evaluation using magnetic resonance imaging. *Foot (Edinb)*. 2013;23(4):115-119. doi:10.1016/j.foot.2013.07.001
14. Guilford JP. *Fundamental Statistics in Psychology and Education*. 1st ed. McGraw-Hill; 1942.
15. Hashimoto T, Sakuraba K. Assessment of effective ankle joint positioning in strength training for intrinsic foot flexor muscles: a comparison of intrinsic foot flexor muscle activity in a position intermediate to plantar and dorsiflexion with that in maximum plantar flexion using needle electromyography. *J Phys Ther Sci*. 2014;26(3):451-454. doi:10.1589/jpts.26.451
16. Holowka NB, Lieberman DE. Rethinking the evolution of the human foot: insights from experimental research. *J Exp Biol*. 2018;221(17):jeb174425. doi:10.1242/jeb.174425
17. Jung DY, Kim MH, Koh EK, Kwon OY, Cynn HS, Lee WH. A comparison in the muscle activity of the abductor hallucis and the medial longitudinal arch angle during toe curl and short foot exercises. *Phys Ther Sport*. 2011;12(1):30-35. doi:10.1016/j.ptsp.2010.08.001
18. Kura H, Luo ZP, Kitaoka HB, An KN. Quantitative analysis of the intrinsic muscles of the foot. *Anat Rec*. 1997;249(1):143-151. doi:10.1002/(SICI)1097-0185(199709)249:1<143::AID-AR17>3.0.CO;2-P
19. 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(1):26. doi:10.1186/1757-1146-7-26
20. 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
21. 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
22. Latey PJ, Burns J, Nightingale EJ, Clarke JL, Hiller CE. 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):28. doi:10.1186/s13047-018-0259-0
23. McKeon PO, Hertel J, Bramble D, Davis I. The foot core system: a new paradigm for understanding intrinsic foot muscle function. *Br J Sports Med*. 2015;49(5):290-290. doi:10.1136/bjsports-2013-092690
24. Olivera ALP, Alzapiedi DF, Solan MC, Karamanidis K, Mileva KN, James DC. Direct muscle electrical stimulation as a method for the in vivo assessment of force production in m. abductor hallucis. *J Biomech*. 2020;100:109606. doi:10.1016/j.jbiomech.2020.109606
25. Refshauge KM, Chan R, Taylor JL, McCloskey DI. Detection of movements imposed on human hip, knee, ankle and toe joints. *J Physiol*. 1995;488(1):231-241. doi:10.1113/jphysiol.1995.sp020961
26. 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):48. doi:10.3390/biology10010048
27. Sakamoto K, Kudo S. Morphological characteristics of intrinsic foot muscles among flat foot and normal foot using ultrasonography. *Acta Bioeng Biomech*. 2020;22(4):161-166.
28. Schuenke M, Schulte E, Schumacher U, eds. Ankle & foot. In: *Atlas of Anatomy With Latin Nomenclature*. 1st ed. Thieme Medical; 2009:400-419.
29. Taş S, Çetin A. Mechanical properties and morphologic features of intrinsic foot muscles and plantar fascia in individuals with hallux valgus. *Acta Orthop Traumatol Turc*. 2019;53(4):282-286. doi:10.1016/j.aott.2019.03.009
30. Tosovic D, Ghebremedhin E, Glen C, Gorelick M, Mark Brown J. The architecture and contraction time of intrinsic foot muscles. *J Electromyogr Kinesiol*. 2012;22(6):930-938. doi:10.1016/j.jelekin.2012.05.002
31. Young A, Stokes M, Crowe M. Size and strength of the quadriceps muscles of old and young women. *Eur J Clin Invest*. 1984;14(4):282-287. doi:10.1111/j.1365-2362.1984.tb01182.x
32. Zelik KE, La Scaleia V, Ivanenko YP, Lacquaniti F. Coordination of intrinsic and extrinsic foot muscles during walking. *Eur J Appl Physiol*. 2015;115(4):691-701. doi:10.1007/s00421-014-3056-x
33. Zhang X, Pauel R, Deschamps K, Jonkers I, Vanwanseele B. Differences in foot muscle morphology and foot kinematics between symptomatic and asymptomatic pronated feet. *Scand J Med Sci Sports*. 2019;29(11):1766-1773. doi:10.1111/sms.13512