Intrinsic foot muscle size can be measured reliably in weight bearing using ultrasound imaging

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Abstract

Background: The intrinsic foot muscles (IFMs) are important contributors to optimal foot function. While assessment of IFM morphology using ultrasound imaging in non-weight bearing has been established, this does not evaluate the foot in its primary functional position of weight bearing.

Research Question: Is ultrasound imaging a reliable and clinically feasible method of measuring IFM morphology in weight bearing, do these measures differ to those from non-weight bearing and are they associated with participant characteristics?

Methods: Ultrasound images were obtained by a single rater from twenty-four healthy participants on two occasions, one week apart. Images were taken in weight bearing (bilateral stance) and non-weight bearing (seated). Cross-sectional area and dorsoplantar thickness of the abductor hallucis muscle, and dorsoplantar thickness of the muscles of the first interstitium were measured from acquired images. A second rater also acquired images at the first session. Participant characteristics included age, height, weight, sex, foot posture and foot mobility.

Results: Measurements of IFM morphology demonstrated high reliability within and between test sessions, as well as between raters (ICCs > 0.8). Our findings suggest that changes of 10-18% could be considered to exceed measurement error. Larger IFM size was related to larger body size (taller, heavier), foot posture (longer foot, higher arch, wider midfoot) and male sex.

Significance: This study is the first to describe a reliable and clinically feasible method of measuring IFM morphology in weight bearing. These measurements could be used in future studies to assess IFM morphology in patient populations and to evaluate the effect of intervention. Body size and foot posture explained between 20 and 41% of the variance in measurements and should be considered when comparing IFM morphology between individuals. The establishment of reliable measurements in weight bearing provides a crucial step towards the future evaluation of IFM function using ultrasound imaging.

Keywords: morphology, abductor hallucis, adductor hallucis, lumbricals, dorsal interossei

Introduction

The intrinsic muscles of the human foot play an integral role in foot stability, shock absorption and force transmission during functional activities [1, 2]. In contrast to extrinsic muscles that originate in the leg, intrinsic foot muscles (IFMs) both originate and insert in the foot and have the anatomical configuration to provide active support the foot's arches [3, 4], particularly the medial longitudinal arch. In support, electromyography studies demonstrate that abductor hallucis, flexor digitorum brevis and quadratus plantae muscles contribute to control of foot posture during standing [5, 6], and are active during stance phase of gait; actively lengthening during early stance and shortening during late stance [1].

Considering the importance of IFMs for optimal foot function, impairments of IFM structure and function have been implicated in lower limb pain and injury [7]. Cross-sectional studies demonstrate differences of IFMs between individuals with and without chronic plantar heel pain [8], hallux valgus [9], chronic ankle instability [10] and diabetes [11]. Thus, it is plausible that assessment and training of IFM function may contribute to effective management of individuals with lower limb disorders.

Measurement of IFM structure and activation is challenging, particularly in the clinical setting. Although several methods to measure strength have been described, these tests recruit both the intrinsic and extrinsic muscles of the foot [12]. Other methods such as computed tomography, magnetic resonance imaging, electromyography and muscle biopsy can differentiate extrinsic and intrinsic muscles, and identify individual IFMs [12]. However, the clinical utility of these methods is limited due to cost, accessibility and invasiveness. Ultrasonography is a non-invasive, widely available method to objectively measure muscle structure [13] and estimate activation [14], and can be applied to measurement of IFMs. Ultrasound measurements of IFM

thickness and cross-sectional area (CSA) are reliable [15-20] and are correlated with strength measures using toe dynamometry[20, 21]. Unfortunately, imaging has predominantly been performed with the patient in non-weight bearing positions, which does not replicate foot function. Only one study has demonstrated reliability in a weight bearing position [16], but required use of customised equipment to enable access for measurement. Finally, the reliability of ultrasound measurements has not been reported for all IFMs; no studies have evaluated adductor hallucis - the second largest IFM and substantial mechanical advantage to control the arch [4].

This study aimed to: (i) develop a clinically feasible method to measure IFM morphology in weight bearing using ultrasound imaging; (ii) establish the reliability, measurement error and minimal detectable change for measurements in both weight bearing and non-weight bearing; and (iii) examine differences between measurements from weight bearing and non-weight bearing positions. A secondary aim was to explore the relationship between measures of IFM morphology and participant characteristics such as age, sex, body size, foot posture and mobility.

Methods

Participants

A convenience sample of 24 participants were recruited from a university staff and student population. Individuals who were aged 18 years or older were eligible to participate, but were excluded if they had experienced a lower limb injury in the preceding twelve months, or had diabetes, a diagnosed joint disease, or a known neurological condition. Volunteers provided written consent and the institutional Human Research Ethics Committee approved the study (#2016-51H).

Ultrasound imaging

LOGIQ S7 Expert (GE Healthcare) ultrasound apparatus equipped with a linear array probe (4.2 – 12.0MHz) was used to obtain ultrasound images of the IFMs. Participants stood in relaxed bilateral stance, with weight evenly distributed between feet. This was selected as a functional position for the foot, whilst reducing the influence of balance that would be required for a single leg stance positions. To improve repeatability across sessions and testers [22], foot position was standardised using a template that aligned the medial borders of each foot parallel and 20 cm apart (to enable access of the ultrasound probe). With the foot flat on the floor, ultrasound imaging was possible from the dorsal and medial aspects of the foot. Pilot testing established that abductor hallucis (ABH) could be imaged from the medial aspect, and the adductor hallucis, dorsal interossei, lumbricals and extensor digitorum brevis muscles from the dorsal aspect. Image quality of muscles of the plantar layer of IFMs, such as the flexor hallucis brevis, flexor digitorum brevis, flexor digiti minimi, abductor digiti minimi, quadratus plantae, and plantar interossei, was poor due to their depth and limited access between the metatarsal bones. Given that the focus of this study was measurement of the IFMs in a functional weight bearing position, we examined the ABH and a single measure of the muscles situated in the first interstitial space (FIS: space between the first and second metatarsals) that included adductor hallucis, first dorsal interossei; first lumbrical. A single summed thickness measure was used as it was difficult to identify fascial boundaries for each muscle because of their complex fascicle structure. Extensor digitorum was not examined as available evidence suggests that its role is primarily involved in extension of the second to fifth toes, rather than supporting the foot in weight bearing [23].

To enable comparison with previous studies, ultrasound images were also obtained with the participant in non-weight bearing. Rather than positioning participants in supine lying (like previous studies), participants were seated with both feet placed on the floor on the standardised template, with ankles positioned in plantargrade, hip and knee joints flexed to 90 degrees, and the upper body weight supported by the participants hands which were placed behind them to ensure minimal weight bearing through the feet. This position was chosen because it: removed the need for specialised apparatus to hold the ankle in plantargrade when positioned in supine lying; ensured that the ankle and foot position was similar to the position used for weight bearing measures; and is more pragmatic for examination of IFMs in a clinical setting, particularly contraction of the IFMs which is less difficult when the foot is in contact with the ground [15].

Placement of the ultrasound probe was based on previously described recommendations for the ABH [18, 19] and FIS [24]. As previous research has indicated that a standardized probe location using anatomical landmarks improves repeatability[18], we modified the existing probe placement procedures to reference all measurements to anatomical landmarks (Table 1). Transverse and longitudinal images of the ABH were obtained to allow measurement of the CSA and dorsoplantar thickness, respectively. Transverse images of the ABH were obtained in the non-weight bearing position only. Longitudinal images of the FIS were obtained to enable measurement of dorsoplantar thickness. For acquisition of all images, the probe was positioned perpendicular to the muscle borders, and light pressure was exerted on the probe to avoid compression of soft tissue. The examiners made depth, focal position and contrast adjustments to optimise the ultrasound image. Each image was acquired three times with removal of the probe between imaging.

Ultrasound images were stored and later measured offline using OsiriX medical imaging software (Geneva, Switzerland). To measure the CSA of the abductor hallucis, the muscle border was traced manually (Table 1). For thickness measurements of ABH and the FIS muscles, manual measurement of the distance between fascial borders at the thickest portion of muscle tissue was performed (Table 1).

Foot posture and mobility

Assessment of foot posture and mobility was performed using a customised foot platform and callipers as previously described [25]. Measurements of total foot length, arch height and midfoot width (both at 50% foot length) were performed with the participant in relaxed bilateral stance. Dorsal arch height and midfoot width were repeated in a non-weight bearing seated position. The difference between non-weight bearing and weight bearing measurements was used to calculate vertical (difference in dorsal arch height) and medial-lateral (difference in midfoot width) midfoot mobility. Foot mobility magnitude was calculated as a composite measure of vertical and medial-lateral mobility of the midfoot. Reliability of these measurements has been established [25].

Experimental procedure

Prior to commencing data collection, two experienced physiotherapists (MMFS, NJC) underwent training sessions together using the standardised protocol regarding patient position, probe location and anatomical landmarks for ultrasound imaging. The two examiners had 8 years (Rater 1) and 1 year (Rater 2) of experience using real-time ultrasound imaging.

Participants attended two testing sessions, one week apart. At the first session, two physiotherapists (Rater 1, Rater 2) obtained images of the IFMs using a standardised protocol.

The order of examiner was randomised. At the second session, a single examiner (Rater 1) repeated the ultrasound imaging, followed by measurement of foot posture and mobility. All measurements were performed on the participant's dominant stance limb (preferred limb when asked to perform a single-leg balance activity). Participant characteristics [sex, age, height, weight, body mass index] were also recorded.

Statistical analysis

Statistical analysis was conducted using IBM SPSS Statistics 24 (IBM Corporation, NY, USA). Intraclass correlation coefficients ($ICC_{(3,1)}$) were used to assess inter-rater reliability, intra-rater within-session repeatability, and intra-rater between-session reliability of IFM measurements from ultrasound images. ICC values were characterised as fair to good (ICC value 0.40 to 0.75) and excellent (ICC value > 0.75)[26]. Standard error of measurement (SEM) was also calculated to provide an indicator of reliability expressed in the same units as the original measurement. The 95% minimal detectable change (MDC_{95}) was calculated to reflect the amount of change required to represent a true change (i.e. exceeding measurement error).

Shapiro Wilk tests confirmed that all data were normally distributed ($\alpha<0.05$). Descriptive statistics were calculated for IFM morphology and participant characteristics [age, height, weight, body mass index, foot posture and mobility]. The thickness measures of ABH and FIS determined from weight bearing and non-weight bearing positions were compared using paired samples t-tests. The association between IFM morphology and participant characteristics was studied using Pearson's correlation coefficient (r) and the amount of variance in IFM morphology explained by participant characteristics was estimated by calculating the coefficient of determination (r^2). Measures of IFM morphology were compared between male

and female participants using analyses of covariance (ANCOVA) with body size and foot posture/mobility used as covariates. Covariates were selected based on the measure with the highest and most consistent correlation to IFM morphology. The alpha level was set at $P<0.05$ for all statistical analyses.

Results

Twenty-four individuals (13 males) participated in the study. The test limb was the right side for 16 (67%) participants. Test sessions were an average of 6.8 days apart (minimum 5 days, maximum 9 days). Table 2 presents descriptive data for the cohort.

Reliability was excellent [26] for all muscles and measurements (Tables 3, 4). Within-session intra-rater ICCs exceeded 0.94 for both Raters, with SEMs and MDCs less than 3.6% and 10.0% of mean values, respectively. Between-session intra-rater ICCs exceeded 0.81, with SEMs less than 6.5% of mean values, and MDCs less than 17.9% of mean values. Inter-rater ICCs exceeded 0.82, with SEMs and MDCs less than 8.2% and 22.6%, respectively. ABH thickness was significantly greater in weight bearing than non-weight bearing (mean difference (95% confidence interval): 0.08cm (0.04 to 0.12), $p = 0.001$) but not the FIS (-0.06cm (-0.13 to 0.001), $p = 0.056$).

Moderate correlations ($r = 0.508$ to 0.619) were observed between FIS thickness and measurements of body size and foot posture (Table 5). Greater thickness was associated with taller height, heavier weight, a longer foot, higher dorsal arch and wider midfoot. ABH thickness was not correlated to majority of the body size and foot posture/mobility measures, but moderate correlations ($r = 0.452$ to 0.639) were observed between CSA and foot posture. Greater ABH CSA was associated with a longer foot and wider midfoot. Age, body mass index

and foot mobility was not associated with IFM morphology, with exception of weight bearing ABH thickness which was correlated to vertical foot mobility. Males had greater thickness of the FIS and larger ABH CSA (Table 6). However, when controlling for weight and total foot length, significant differences were only observed for FIS thickness.

Discussion

This study presents a clinically feasible, non-invasive method to measure IFM morphology in a weight bearing position using ultrasound imaging. This is the first study to evaluate the reliability of ultrasound measurements of FIS thickness, but for ABH our findings corroborate previous reports (Tables 3, 4). The results indicate excellent reliability [26] in both weight bearing and non-weight bearing positions for comparisons within and between sessions, as well as between raters. Using a standardised protocol for patient/foot position, and probe location using anatomical landmarks and distances, likely contributed to the high reliability. Of note, our calculations that are based on comparison of a single measurement had similar reliability to previous studies that used the average of three measurements [15-17]. Single measures may have greater clinical utility.

MDCs reported in our study can be used to identify differences between individuals or changes over time that could be considered to exceed measurement error. This has not been previously reported for FIS, but for ABH our measurement error is comparable with previous reports (CSA 0.26cm^2 or 10%; thickness 0.18cm or 14%)[15]. When comparing between individuals/populations, differences greater than 10% can be considered to exceed measurement error. In populations where IFM atrophy has been reported (chronic plantar heel pain [8], hallux valgus [9], chronic ankle instability [10] and diabetes [11]), our results could

be used to identify changes over time e.g. post intervention. Changes greater than 14% in FIS or 18% in ABH could be considered to exceed measurement error.

Comparison between measurements of IFM morphology from images acquired in weight bearing and non-weight bearing positions, indicate that for the ABH muscle dorsoplantar thickness was 7.2% greater in weight bearing. This finding is consistent with that reported previously (mean difference 0.15cm, 11.2% mean values)[16]. The greater muscle thickness likely reflects an increase in muscle activation to support the arch during postural/load demands of weight bearing [5]. Although an increase in activation of the muscles of the FIS might also be expected, it is possible that surrounding musculature and/or overlying fascial boundaries may have limited dorsoplantar expansion of these muscles, and may explain the negligible change in muscle thickness (1.6%) that we observed. Small changes in thickness have been reported for other muscles located within the foot (i.e. 4% increase in flexor digitorum brevis thickness and 2% increase in quadratus plantae thickness)[16].

This is the first study to describe a weight bearing assessment of IFM morphology that is easily applied and reproducible in the clinical setting. It addresses the limitations of previous studies, such as; (i) removal of the need for specialised equipment, (ii) quantification of measurement error, and (iii) identification of associated participant characteristics. The major advantage of establishing a method of IFM measurement in a weight bearing position is that it allows evaluation in a functional position and provides an opportunity to explore the relationship between IFMs and foot function. Although the measurements described in the current study were obtained during a static condition and thereby provide an indication of muscle morphology, they could be applied to a quasi-dynamic condition (such as contraction of the IFM in standing) which may provide an indication of neuromotor control. The use of

ultrasound imaging to evaluate neuromotor control has been previously validated against measures made with electromyography at other areas of the body, including the leg[14]. Fraser et al[15] recently explored changes in IFM morphology during contraction and reported that performance of contractions in a supine position was difficult for patients. Both of the assessments in seated non-weight bearing and standing weight bearing positions described in the present study address this limitation as the foot is in contact with the ground. Future research could use electromyography to validate the use of ultrasound imaging to evaluate neuromotor control of the IFM.

This study is the first to report that body size and foot posture explained between 25-38% of the variance in measurements of FIS thickness. Whilst ABH thickness and CSA was not related to body size, foot posture explained between 20-40% of the variance in measurements of CSA, which supports previous reports [20, 27, 28]. What remains unclear is whether the association between IFM morphology and foot posture is due to anatomical dimensions (body size) with some studies reporting significant associations to foot posture even when controlling for body size[27], whilst others report that associations become non-significant when controlling for body size[20]. It is possible that the contrasting findings are explained by different measurements of foot posture (e.g foot posture index, transverse arch height, medial longitudinal arch height) and/or positions (e.g. 10% and 90% body weight, bilateral standing, seated/non-weight bearing). In our study, age was not related to either FIS or ABH morphology which supports previous reports in healthy adults that include broader age ranges beyond 65 years[20, 29]. We found that when controlling for body size and foot posture, FIS thickness, but not ABH, was greater in males compared with females. Although this appears to contrast a previous report that ABH CSA is larger in males compared to females [21], those authors did not control for sex differences in height and weight, which were reported in their

cohort. Greater FIS thickness in males may be explained by sex differences in foot loading patterns during gait that have been previously reported[30]. Specifically, males exhibited greater excursion of the centre of pressure progression angle during forefoot contact, forefoot flat and forefoot push off phases[30]. Plausibly this would require greater contribution from muscles that act to stabilise the forefoot, such as adductor hallucis and the dorsal interossei. However, this hypothesis is based on anatomical evidence as no electromyographic studies have reported the function of these muscles during gait, and further investigation is required.

This pilot study included a relatively small convenience sample of healthy participants and larger samples including patient populations are required to extrapolate our measurement characteristics to those groups. Using a weight bearing position with the foot in contact with the ground we were not able to measure all IFM. However, the IFM that we evaluated have been previously associated with hallux valgus[9], chronic ankle instability [10] and the diabetic foot[11], which supports their potential clinical relevance.

In conclusion, the results of this study show that ultrasound measurements of the IFM are reliable in both weight bearing and non-weight bearing positions, when performed using a standardised protocol. These measures are clinically applicable, non-invasive and require no specialised equipment aside from real-time ultrasound apparatus. MDCs reported provide an indication of the amount of difference between individuals or change over time (e.g. post intervention) that should be considered to exceed error. Patient characteristics such as sex, body size and foot posture should be considered when comparing IFM morphology between individuals. Further studies are needed to establish reliability and normative values across patient populations, and to explore the use of ultrasound imaging in the evaluation of IFM contraction.

List of abbreviations

ABH: Abductor hallucis

CSA: Cross-sectional area

FIS: First interstitial space

ICC: Intra-class correlation coefficient

IFM: Intrinsic foot muscles

MDC: Minimal detectable change

NWB: Non-weight bearing

SEM: Standard error of measurement

WB: Weight bearing

Authors' contributions

MMFS – conception and design of the study, acquisition of data, analysis and interpretation of data, drafting the article, final approval of the version to be submitted.

JAH – conception and design of the study, analysis and interpretation of data, article revision, final approval of the version to be submitted.

PWH – analysis and interpretation of data, article revision, final approval of the version to be submitted.

NJC – conception and design of the study, acquisition of data, analysis and interpretation of data, manuscript preparation, drafting the article and revision, final approval of the version to be submitted.

Declarations of interest

None

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References

[1] Kelly LA, Lichtwark G, Cresswell AG. Active regulation of longitudinal arch compression and recoil during walking and running. J R Soc Interface. 2015;12:20141076.

[2] Okamura K, Kanai S, Hasegawa M, Otsuka A, Oki S. The effect of additional activation of the plantar intrinsic foot muscles on foot dynamics during gait. Foot. 2017;34:1-5.

[3] Tosovic D, Ghebremedhin E, Glen C, Gorelick M, Mark Brown J. The architecture and contraction time of intrinsic foot muscles. J Electromyogr Kinesiol. 2012;22:930-8.

[4] Kura H, Luo ZP, Kitaoka HB, An KN. Quantitative analysis of the intrinsic muscles of the foot. The Anatomical Record. 1997;249:143-51.

[5] Kelly LA, Cresswell AG, 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.

[6] Kelly LA, Kuitunen S, Racinais S, Cresswell AG. Recruitment of the plantar intrinsic foot muscles with increasing postural demand. Clin Biomech. 2012;27:46-51.

[7] Latey PJ, Burns J, Hiller CE, Nightingale EJ. Relationship between foot pain, muscle strength and size: a systematic review. Physiotherapy. 2017;103:13-20.

[8] Cheung RT, Sze LK, Mok NW, Ng GY. Intrinsic foot muscle volume in experienced runners with and without chronic plantar fasciitis. J Sci Med Sport. 2016;19:713-5.

[9] Stewart S, Ellis R, Heath M, Rome K. Ultrasonic evaluation of the abductor hallucis muscle in hallux valgus: a cross-sectional observational study. Bmc Musculoskel Dis. 2013;14:45.

[10] Feger MA, Snell S, Handsfield GG, Blemker SS, Wombacher E, Fry R, et al. Diminished Foot and Ankle Muscle Volumes in Young Adults With Chronic Ankle Instability. Orthop J Sports Med. 2016;4:2325967116653719.

[11] Morrison T, Jones S, Causby RS, Thoirs K. Can ultrasound measures of intrinsic foot muscles and plantar soft tissues predict future diabetes-related foot disease? A systematic review. Plos One. 2018;13:e0199055.
[12] Soysa A, Hiller C, Refshauge K, Burns J. Importance and challenges of measuring intrinsic foot muscle strength. J Foot Ankle Res. 2012;5:29.
[13] Pretorius A, Keating JL. Validity of real time ultrasound for measuring skeletal muscle size. Physical Therapy Reviews. 2008;13:415-26.
[14] Hodges PW, Pengel LHM, Herbert RD, Gandevia SC. Measurement of muscle contraction with ultrasound imaging. Muscle & Nerve. 2003;27:682-92.
[15] Fraser JJ, Mangum LC, Hertel J. Test-retest reliability of ultrasound measures of intrinsic foot motor function. Phys Ther Sport. 2018;30:39-47.
[16] Battaglia PJ, Mattox R, Winchester B, Kettner NW. Non-Weight-Bearing and Weight-Bearing Ultrasonography of Select Foot Muscles in Young, Asymptomatic Participants: A Descriptive and Reliability Study. J Manipulative Physiol Ther. 2016;39:655-61.
[17] Crofts G, Angin S, Mickle KJ, Hill S, Nester CJ. Reliability of ultrasound for measurement of selected foot structures. Gait Posture. 2014;39:35-9.
[18] Mickle KJ, Nester CJ, Crofts G, Steele JR. Reliability of ultrasound to measure morphology of the toe flexor muscles. J Foot Ankle Res. 2013;6:12.
[19] Cameron AF, Rome K, Hing WA. Ultrasound evaluation of the abductor hallucis muscle: Reliability study. J Foot Ankle Res. 2008;1:12.
[20] 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;11:28.

[21] 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;28:14-9.

[22] McPoil TG, Carrell D, Ehlers D, Kuhlman H, Mufti J, Pomeroy M, et al. Does foot placement affect the reliability of static foot posture measurements? J Am Podiatr Med Assoc. 2014;104:34-42.

[23] Zelik KE, La Scaleia V, Ivanenko YP, Lacquaniti F. Coordination of intrinsic and extrinsic foot muscles during walking. Eur J Appl Physiol
. 2015;115:691-701.

[24] Severinsen K, Obel A, Jakobsen J, Andersen H. Atrophy of foot muscles in diabetic patients can be detected with ultrasonography. Diabetes Care. 2007;30:3053-7.

[25] McPoil TG, Vicenzino B, Cornwall MW, Collins N, Warren M. Reliability and normative values for the foot mobility magnitude: a composite measure of vertical and medial-lateral mobility of the midfoot. J Foot Ankle Res. 2009;2:6.

[26] Rosner B. Fundamentals of Biostatistics. 7th ed. Boston: Brooks/Cole, Cengage Learning; 2011.

[27] Nakayama Y, Tashiro Y, Suzuki Y, Kajiwara Y, Zeidan H, Kawagoe M, et al. Relationship between transverse arch height and foot muscles evaluated by ultrasound imaging device. J Phys Ther Sci. 2018;30:630-5.

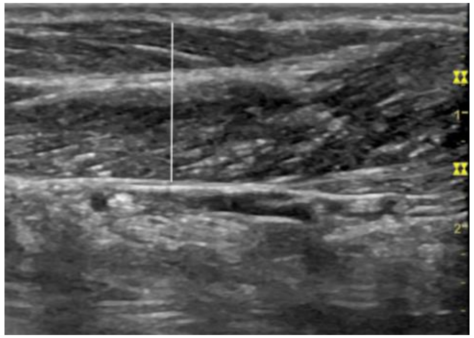
[28] Angin S, Mickle KJ, Nester CJ. Contributions of foot muscles and plantar fascia morphology to foot posture. Gait Posture. 2018;61:238-242.

[29] Mickle KJ, Angin S, Crofts G, Nester CJ. Effects of Age on Strength and Morphology of Toe Flexor Muscles. Journal Orthop Sports Phys Ther. 2016;46:1065-70.

[30] Chiu MC, Wu HC, Chang LY. Gait speed and gender effects on center of pressure progression during normal walking. Gait Posture. 2013;37:43-8.

Table 1. Ultrasound imaging protocol

	FIS THICKNESS	ABH THICKNESS	ABH CSA
PROBE ORIENTATION			
LANDMARK REFERENCE	Probe aligned between 1st and 2nd metatarsal bones. Distal probe edge placed on a line drawn between the 1st and 2nd metatarsophalangeal joint lines. [24]	Line drawn parallel to the long axis of the foot at a point that is 50% distance between the inferior aspect of medial malleolus and supporting surface. Top edge of probe placed over this line, with the middle of the probe placed over the vertical line of the anterior malleolus (CSA marker). [18, 19]	Line drawn in an inferior direction from the most anterior aspect of the medial malleolus. Middle of the probe placed over this line. [18, 19]

IMAGE MEASUREMENT			

CSA Cross-Sectional Area

Table 2. Descriptive data.

	Mean (SD)	Range
Participant characteristics		
Age (years)	31 (9)	18 - 53
Height (m)	1.7 (0.1))	1.5 – 1.9
Weight (kg)	74.7 (13.3)	54.3 – 112.7
BMI (kg/m^2)	24.8 (3.2)	20.2 – 34.6
Foot posture and mobility		
Total foot length (cm)	25.9 (1.8)	22.2 – 28.2
Arch height – WB (mm)	66.3 (6.2)	56.2 – 80.0
Arch height – NWB (mm)	78.8 (6.3)	66.0 – 90.5
Midfoot width – WB (mm)	85.1 (8.6)	72.0 – 100.9
Midfoot width – NWB (mm)	76.0 (6.6)	63.4 – 88.3
Arch height difference	12.5 (2.7)	8.9 – 20.7
Midfoot width difference	9.1 (2.9)	3.0 – 14.7
Foot mobility magnitude	15.6 (3.3)	10.3 – 25.4
IFM morphology		
FIS thickness – NWB (cm)	3.69 (0.43)	2.81 – 4.49
FIS thickness – WB (cm)	3.63 (0.39)	2.95 – 4.46
ABH CSA (cm^2)	2.12 (0.66)	0.60 – 3.08
ABH thickness – NWB (cm)	1.11 (0.21)	0.61 – 1.57
ABH thickness – WB (cm)	1.19 (0.22)	0.73 – 1.54

Legend: ABH Abductor hallucis, FIS First interstitial space, CSA Cross-Sectional Area, WB Weight bearing, NWB Non-Weight Bearing.

Table 3. Intra-rater reliability.

	Within session reliability							Between session reliability (Rater 1)					
	Rater 1			Rater 2				Session 1	Session 2				
	ICC	SEM	MDC_{95}	ICC	SEM	MDC_{95}	ICC previous studies	Mean (SD)	Mean (SD)	ICC	SEM	MDC_{95}	ICC previous studies
FIS Thickness NWB (cm)	0.98	0.05	0.14	0.98	0.06	0.16	N/A	3.74 (0.35)	3.68 (0.44)	0.81	0.17	0.48	N/A
FIS Thickness WB (cm)	0.97	0.05	0.14	0.94	0.08	0.22	N/A	3.62 (0.32)	3.60 (0.39)	0.87	0.13	0.36	N/A
ABH CSA (cm^2)	0.99	0.07	0.21	0.99	0.06	0.10	0.95 [19]	2.13 (0.71)	2.13 (0.65)	0.97	0.13	0.35	0.79 to 0.98 [15, 18-20]
ABH Thickness NWB (cm)	0.97	0.03	0.10	0.97	0.04	0.11	0.97 [19]	1.12 (0.21)	1.12 (0.23)	0.92	0.06	0.17	0.88 to 0.98 [15, 18, 19]
ABH Thickness WB (cm)	0.97	0.04	0.10	0.99	0.03	0.08	N/A	1.20 (0.23)	1.19 (0.21)	0.88	0.08	0.21	N/A

Within-session reliability for Rater 1 and Rater 2 is a comparison of the three images captured at session 1 by each rater.

Between-session reliability for Rater 1 is a comparison of a single image from session one and session two.

Legend: N/A = Not available / not previously reported, ICC Intraclass Correlation Coefficient, SEM Standard Error of Measurement, MDC_{95} 95% Minimal Detectable Change.

Table 4. Inter-rater reliability.

	Rater 1 Mean (SD)	Rater 2 Mean (SD)	ICC	SEM	MDC_{95}	ICC from previous studies
FIS Thickness NWB (cm)	3.74 (0.35)	3.78 (0.41)	0.86	0.14	0.40	N/A
FIS Thickness WB (cm)	3.62 (0.32)	3.70 (0.33)	0.92	0.09	0.26	N/A
ABH CSA (cm2)	2.13 (0.71)	2.16 (0.69)	0.98	0.10	0.29	0.91 to 0.95 [16, 17]
ABH Thickness NWB (cm)	1.12 (0.21)	1.14 (0.22)	0.85	0.08	0.23	0.72 to 0.92 [16, 17]
ABH Thickness WB (cm)	1.20 (0.23)	1.23 (0.24)	0.82	0.10	0.28	0.61 [16]

Comparison of a single image from Rater 1 and Rater 2 at session 1.

Legend: FIS First interstitial space, ABH Abductor hallucis, N/A Not Available / not previously reported, ICC Intraclass Correlation Coefficient, SEM Standard Error of Measurement, MDC_{95} 95% Minimal Detectable Change.

Table 5. Pearson's correlation coefficient (r) between measures of IFM and participant characteristics.

Variable	FIS NWB		FIS WB		ABH NWB		ABH WB		ABH CSA	
	r	P	r	P	r	P	r	P	r	P
Age	-0.056	0.794	-0.129	0.549	0.049	0.820	0.141	0.511	-0.074	0.729
Body size										
Height	0.545**	0.006	0.579**	0.003	0.328	0.118	0.260	0.221	0.361	0.361
Weight	0.619**	0.001	0.568**	0.004	0.358	0.086	0.399	0.054	0.394	0.057
Body mass index	0.398	0.054	0.310	0.140	0.213	0.317	0.316	0.133	0.230	0.279
Foot posture										
Total foot length	0.568**	0.004	0.591**	0.002	0.303	0.150	0.237	0.264	0.452*	0.027
Arch height NWB	0.558**	0.005	0.588**	0.003	0.421*	0.040	0.380	0.067	0.384	0.064
Midfoot width NWB	0.508*	0.011	0.579**	0.003	0.392	0.058	0.348	0.096	0.639**	0.001
Arch height WB	0.535**	0.007	0.602**	0.002	0.269	0.203	0.183	0.393	0.300	0.154
Midfoot width WB	0.521**	0.009	0.544**	0.006	0.332	0.113	0.321	0.126	0.597**	0.002
Foot mobility										
Arch height difference	0.060	0.781	-0.024	0.910	0.354	0.089	0.457*	0.025	0.198	0.354

Midfoot width difference	0.391	0.059	0.296	0.160	0.090	0.676	0.159	0.459	0.316	0.133
Foot mobility magnitude	0.220	0.301	0.123	0.567	0.279	0.186	0.383	0.065	0.282	0.181

**P-value significant at 0.01 level, *P-value significant at 0.05 level.

Legend: FIS First interstitial space, ABH Abductor hallucis, NWB Non-weight bearing, WB Weight bearing.

Table 6. IFM morphology for male and female participants.

	Unadjusted means (SD)				*Adjusted means (SD)*			
	Male	Female	Mean difference (95% CI)	P	*Male*	*Female*	*Mean difference (95% CI)*	*P*
FIS NWB	3.98 (0.35)	3.35 (0.23)	0.63 (0.37 to 0.88)**	<0.001	*3.92 (0.43)*	*3.42 (0.45)*	*0.49 (0.03 to 0.95)**	*0.039*
FIS WB	3.88 (0.33)	3.33 (0.18)	0.56 (0.33 to 0.78)**	<0.001	*3.83 (0.39)*	*3.38 (0.41)*	0.45 (0.03 to 0.88)*	*0.036*
ABH NWB	1.16 (0.19)	1.06 (0.22)	0.10 (-0.07 to 0.28)	0.232	*1.08 (0.29)*	*1.15 (0.30)*	-0.07 (-0.37 to 0.24)	*0.666*
ABH WB	1.24 (0.21)	1.13 (0.22)	0.10 (-0.08 to 0.29)	0.256	*1.16 (0.30)*	*1.22 (0.31)*	*-0.06 (-0.39 to 0.26)*	*0.681*
ABH CSA	2.42 (0.57)	1.77 (0.61)	0.65 (0.15 to 1.15)*	0.014	*2.31 (0.85)*	*1.90 (0.89)*	*0.41 (-0.51 to 1.33)*	*0.362*

Adjusted means for covariates of weight (74.71kg) and total foot length (25.89cm).

Legend: FIS First interstitial space, ABH Abductor hallucis, NWB Non-weight bearing, WB Weight bearing.