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An investigation of the relationship between plantar pressure distribution and the morphologic and mechanic properties of the intrinsic foot muscles and plantar fascia^{*}

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ABSTRACT

Background: The purpose of this study was to investigate the relationship between plantar pressure distribution and the stiffness, thickness, and cross-sectional area of the plantar fascia (PF) and abductor hallucis (AbH), flexor hallucis brevis (FHB), and flexor digitorum brevis (FDB) muscles.

Methods: The present study included a total of 41 healthy females between the ages of 20 and 34 years. Plantar pressure during static standing position was measured using a pedobarography system (MatScan, Tekscan, Inc., South Boston, Massachusetts, USA). Peak pressure, mean pressure, maximum force (Max-F), contact area (Con-A), pressure time integral, and force time integral (FTI) were measured. The thickness, cross-sectional area and stiffness of the intrinsic foot muscles and PF were measured using an ACUSON S3000 Ultrasound System and a 9L4 probe (4–9 MHz) (Siemens Medical Solution, Mountain View, CA, USA). Shear Wave Velocity (SWV) of the intrinsic foot muscles and PF was measured using a customized software program (Virtual Touch Imaging and Quantification; Siemens Medical Solution).

Results: Con-A had a moderate correlation with the thickness and cross-sectional area of PF, AbH, FHB, and FDB. A fair to moderate correlation was found between heel Max-F and the thickness and cross-sectional area of PF, AbH, FHB, and FDB. There is no significant correlation between the SWV of the assessed tissues and plantar pressure distribution parameters. Body mass and BMI had a fair to good correlation with Mean-P, Con-A, heel Max-F, midfoot Max-F, metatarsal Max-F, FTI, thickness, and cross-sectional area of the PF and assessed muscles.

Significance: The results suggest that abnormal force, contact area, and higher body mass may cause hypertrophy of the PF and foot intrinsic muscles.

1. Introduction

Plantar pressure measurement has been used for a long time to assess and manage foot and lower extremity disorders associated with the orthopedic and neurological system. Plantar pressure is an important component affecting foot and ankle function. Changes in plantar pressure distribution could cause a decrease in foot function, such as support and flexibility abilities during walking, running, standing, and other functional activities [1,2]. In addition, lower-extremity posture is related to plantar pressure distribution [3]. Because of these reasons, changes in foot pressure may cause an abnormal lower extremity alignment and abnormal stress on the foot and related structures, and it may cause many orthopedic disorders such as plantar fasciitis and knee

pain [1,3].

There are several studies in the literature investigating the relationship between plantar pressure and foot posture abnormalities (flat foot, hallux valgus, etc.), demographic features (age, body mass, etc.), and different pathological conditions (plantar fasciitis, patellofemoral pain syndrome, etc.) [1,4–7]. Morphologic and mechanical properties of the plantar fascia (PF) and intrinsic foot muscles may be other important factors affecting the plantar pressure distribution because the primary task of the intrinsic foot muscles and PF is to stabilize the foot arches [8]. Previous studies have shown the relationship of the intrinsic foot muscles and the PF with foot posture and foot function. For example, Taş et al. [9] reported that individuals with flat foot had higher AbH muscle thickness. Moreover, Goldmann et al. [10] found that an

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increase in toe flexor muscle strength could make a contribution to an athlete's performance enhancement. In addition, Suponitsky et al. [11] indicated that the tibialis anterior and peroneus muscles fatigue could cause an increase in postural sway during single-leg standing. Even though a few studies in the literature have investigated the relationship of the PF and intrinsic foot muscles with foot posture and foot function, to the best of our knowledge, there exists no study investigating the relationship between plantar pressure and morphological and mechanical properties of the PF and intrinsic foot muscles. Identifying a possible relationship of the morphological and mechanical properties of the PF and foot muscles with plantar pressure may help to better understand the factors causing or resulting from abnormal plantar pressure related to foot structures, and also to develop better training or treatment strategies. We hypothesized that lower stiffness, thickness, and cross-sectional area of the PF, AbH, FHB, and FDB muscles would be related to abnormal plantar pressure. The purpose of this study was to investigate the relationship between plantar pressure distribution and the stiffness, thickness, and cross-sectional area of the PF and abductor hallucis (AbH), flexor hallucis brevis (FHB), and flexor digitorum brevis (FDB) muscles.

2. Methods

2.1. Sample size calculation

The sample size was calculated by using the SPSS Sample Power 3.0 software (IBM Corporation, Armonk, NY). The calculations were based on the expected correlation coefficient of 0.50, assumed an alpha level (α) of 0.05 and the desired power (β) of 80%. The estimated sample size was calculated to be of at least 29 participants [12].

2.2. Participants

The present study was designed a correlation study. The present study included a total of 41 healthy females between the ages of 20 and 34 years. The study was carried out only in young females with a normal weight, because sex, age, and overweight/obesity could affect plantar pressure distribution and/or muscle morphology [6,13,14]. Participants, whose body mass index were under 25 kg/m^2 , were accepted as a normal weight. Participants were excluded from the study if they met any of the following exclusion criteria: (1) lower extremities orthopedic injuries, such as plantar fasciitis, tendinopathy, bursitis, or ligament injuries, (2) a history of lower extremities surgery or major trauma, (3) rheumatic diseases involving joints in the lower extremities, (4) a systemic disease, such as diabetes and/or connective tissue disorders, which may affect the individual's plantar pressure distribution or/and morphological and mechanical properties of the intrinsic foot muscles and PF. Required permission was obtained from the Non-Invasive Clinical Research Ethics Board of Faculty of Medicine, Hacettepe University with decision dated 12 June 2018 and numbered GO 18/564-03. Participants of the study provided oral and written consent before involvement.

2.3. Plantar pressure measurement

Plantar pressure during static standing position was measured using the MatScan system (Tekscan, Inc., South Boston, Massachusetts, USA). The MatScan system was reported as a reliable and valid system for measuring the plantar pressure distribution [15]. The sensing area of the device is $17.16 \times 14.52''$ ($435.9 \times 368.8 \text{ mm}$) and its pressure range is 125 psi/862 kPa. After calibration based on the manufacturer recommendations, the plantar pressure of the individuals during static standing position was measured with bare feet. Recordings were made at 50 Hz for 30 s, and the analysis was made using the FootMat™ for Clinicians software.

The peak pressure (Peak-P, kPa), mean pressure (Mean-P, kPa),

maximum force (Max-F, lbs), contact area (Con-A, cm^2), pressure time integral (PTI, $\text{kPa} \cdot \text{sn}$), and force time integral (FTI, $\text{lbs} \cdot \text{sn}$) were measured for each participant.

2.4. Ultrasonic examinations

The thickness, cross-sectional area and stiffness of the intrinsic foot muscles and PF were measured using an ACUSON S3000 Ultrasound System and a 9L4 probe (4–9 MHz) (Siemens Medical Solution, Mountain View, CA, USA). Ultrasonography was reported as a reliable method measuring the thickness and/or cross-sectional area of the intrinsic foot muscles and PF [16]. In addition, Sheer-Wave Elastography, which has been reported to be reliable as a new imaging method based on ultrasonography [17], was used to assess the stiffness of the selected soft tissues. Stiffness, thickness and, cross-sectional area measurements of FHB and FDB were measured as the participants in the prone position with 90 degrees of knee flexion and neutral ankle position. AbH stiffness, thickness, and cross-sectional area measurements were performed when the subjects were in the side-lying position and the ankle was in the neutral position. PF stiffness and thickness measurements were performed as the participants in the prone position with 90 degrees of knee flexion and neutral ankle position. For the stiffness, thickness, and cross-sectional area measurements of the AbH, FHB, and FDB, the probe placed along the direction of the muscle fiber (Fig. 1). Shear Wave Velocity (SWV) of the intrinsic foot muscles and PF was measured using a customized software program (Virtual Touch Imaging and Quantification; Siemens Medical Solution). The thickness, cross-sectional area and stiffness of the selected tissues were calculated by taking the average of three successive measurements performed.

2.5. Data analysis

Statistical analyses were carried out using SPSS for Windows, version 18. The visual (histograms, probability plots) and analytical methods (Kolmogorov-Smirnov/Shapiro-Wilk's test) were used to determine whether or not the parameters were normally distributed. Demographic data and the assessed parameters were presented using mean and standard deviation (SD). As the assessed parameters were non-normally distributed, the Spearman's test was used to calculate the correlation coefficients for relations between parameters. For statistical significance, type I error level was set as 5%. Correlation analysis results were classified as follows: 0.00–0.20 (poor correlation), 0.21–0.40 (fair correlation), 0.41–0.60 (moderate correlation), 0.61–0.80 (good correlation), and 0.81–1.00 (very good correlation).

3. Results

Each parameter measured including demographic data and the results of the ultrasonographic and pedographic analyses are given in Table 1.

The correlation analysis revealed that no correlation was found between Peak-P and Mean-P values and the thickness, cross-sectional area and stiffness of the PF and assessed muscles. Con-A had a moderate correlation with the thickness and cross-sectional area of PF, AbH, FHB, and FDB, but not with the stiffness of PF, AbH, FHB, and FDB. A fair to moderate correlation was found between heel Max-F and the thickness and cross-sectional area of PF, AbH, FHB, and FDB, whereas no correlation was found between heel Max-F and the stiffness of the PF, AbH, FHB and FDB muscles. FTI had a fair to moderate correlation with the thickness and cross-sectional area of PF, AbH, FHB, and FDB, but not with the stiffness of AbH, FHB, and FDB. Body mass and BMI had a fair to good correlation with Mean-P, Con-A, heel Max-F, midfoot Max-F, metatarsal Max-F, FTI, and the thickness and cross-sectional area of the PF and assessed muscles. Age was not correlated with pedographic analyses results as well as ultrasonographic measurements results (Table 2).

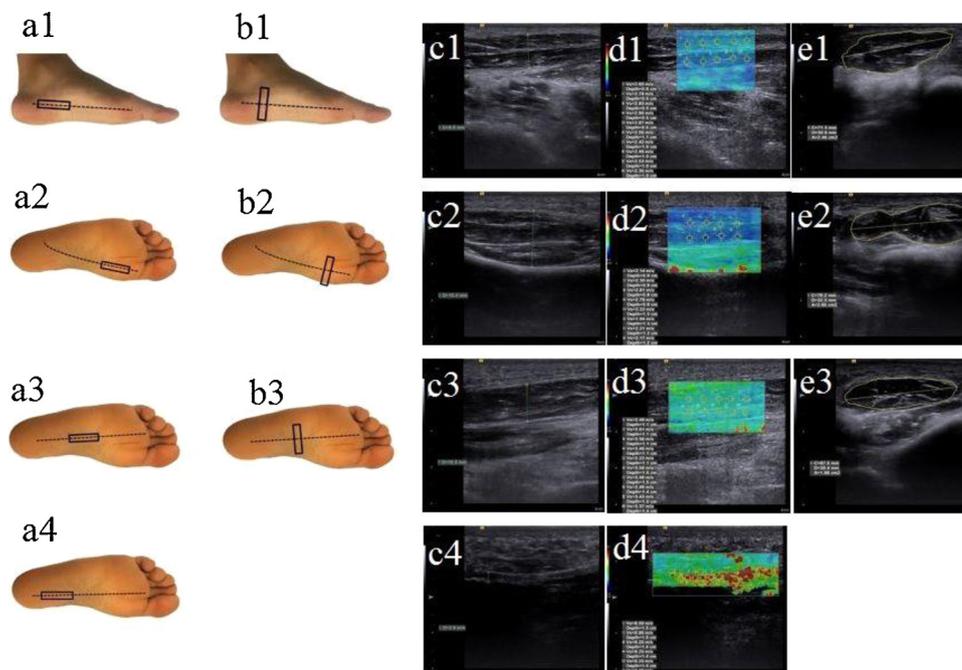


Fig. 1. Probe location and ultrasound imaging measurements. (a) Probe position of the AbH (a1), FHB (a2), FDB (a3) and PF (a4) at thickness and stiffness measurements; (b) Probe position of the AbH (b1), FHB (b2) and FDB (b3) at cross-sectional area measurements; (c) 2-dimensional ultrasound image of the AbH (c1), FHB (c2), FDB (c3) and PF (c4) at thickness measurements; (d) Shear-wave elastography image of the AbH (d1), FHB (d2), FDB (d3) and PF (d4) at stiffness measurements; (e) 2-dimensional ultrasound image of AbH (e1), FHB (e2) and FDB (e3) at cross-sectional area measurements. Regions of interest were placed and corresponding shear wave velocity (m/sec) was recorded. Abductor hallucis, AbH; flexor hallucis brevis, FHB; flexor digitorum brevis, FDB; PF, plantar fascia.

Table 1
Mean, standard deviation, and minimum and maximum values of the assessed parameters (n = 41).

Parameters	Mean ± SD	Minimum-Maximum
Demographic data		
Age (years)	26.9 ± 3.73	20-34
Height (m)	1.63 ± 0.05	1.51-1.75
Weight (kg)	58.3 ± 8.8	43.3-75.4
BMI (kg ² /m)	21.9 ± 2.9	16.4-24.9
Thickness of selected tissues (mm)		
Plantar fascia	3.1 ± 0.4	2.5-3.8
Abductor hallucis	10.5 ± 2.1	5.9-15.0
Flexor hallucis brevis	15.0 ± 1.7	12.4-19.7
Flexor digitorum brevis	9.0 ± 1.4	6.0-11.6
Cross-sectional area (cm ²)		
Abductor hallucis	1.7 ± 0.4	0.9-2.5
Flexor hallucis brevis	2.0 ± 0.5	1.2-3.1
Flexor digitorum brevis	1.8 ± 0.4	1.0-2.4
SWV of selected tissues (m/sec)		
Plantar fascia	7.7 ± 1.1	5.3-9.4
Abductor hallucis	2.7 ± 0.3	2.1-3.6
Flexor hallucis brevis	2.5 ± 0.4	2.1-3.4
Flexor digitorum brevis	3.3 ± 0.3	2.4-3.6
Plantar pressure		
Peak pressure(kPa)	139.9 ± 40.0	77.0-229.0
Mean pressure (kPa)	110.8 ± 30.5	55.0-171.0
Contact area (cm ²)	87.0 ± 11.1	61.8-113.5
Heel maximum force (lbs)	33.0 ± 10.4	14.7-56.6
Midfoot maximum force (lbs)	21.3 ± 10.3	6.1-60.5
Metatarsal maximum force (lbs)	32.5 ± 12.1	10.5-78.3
Force time integral (lbs*sn)	369.3 ± 61.4	274.7-535.8
Pressure time integral (kPa*sn)	188.2 ± 14.4	157.0-221.0

SWV, Shear-Wave Velocity; BMI, Body mass index.

4. Discussion

The purpose of present study was to investigate the relationship between plantar pressure distribution and the thickness, cross-sectional area and stiffness of the PF and intrinsic foot muscles. It was hypothesized that lower stiffness, thickness, and cross-sectional area of the PF, AbH, FHB, and FDB muscles would be related to abnormal plantar pressure distribution. The hypothesis is based on the idea that lower thickness, cross-sectional area and/or stiffness of these structures

may cause unstable foot, which may cause abnormal plantar pressure distribution, because thickness and cross-sectional area are related to muscle function such as muscle strength [18]. In addition, a decrease in the stiffness of soft tissues could cause a decrease in joint stabilization, which may cause a decrease in the resisting capacity against external loading [19]. Different from the hypothesis of the present study, it was found that peak and mean pressure values are not related to thickness, cross-sectional area of the PF and intrinsic muscles. Moreover, the stiffness of these structures does not affect the results of the plantar pressure analysis. Furthermore, contrary to the hypothesis, the results of the present study show that there is a significant positive correlation between maximum force, contact area, and foot-time integral and the thickness and cross-sectional area of these structures. Abnormal pressure and force distribution on the foot may increase the loading on the intrinsic foot muscles and PF, and it may cause hypertrophy of these structures. Similarly, previous studies have investigated the morphology of the foot muscles in foot posture deformities causing changes in foot pressure distribution such as flat foot [9,20]. They reported hypertrophy of intrinsic foot muscles in individuals with flat foot [9,20]. On the other hand, it may be true that hypertrophy of the intrinsic foot muscles and PF may cause an increase in maximum force, contact area, and foot-time integral, but it doesn't seem likely. The primary task of the intrinsic foot muscles and PF is to stabilize the foot arches [8]. It has been reported that strengthening the intrinsic foot muscles can increase the height of the medial longitudinal arch [21]. Furthermore, Headlee et al. [22] reported that the fatigue of the intrinsic foot muscles via repetitive isotonic flexion contractions causes a decrease in the height of the medial longitudinal arch. It is well known that a decrease in the height of the medial longitudinal arch can cause an increase in foot contact area and contact force [23]. Because of these reasons, it is more likely that higher maximum force, contact area, and foot-time integral cause the hypertrophy of the PF and intrinsic foot muscles rather than vice versa.

On the other hand, it was found that higher body mass and BMI are related to higher pressure, force, contact area, force-time integral as well as higher thickness and cross-sectional area of the assessed soft tissues. The results suggest that the increased loading because of higher body mass may cause an increase in pressure, force, contact area, and force-time integral, and it may cause the hypertrophy of the intrinsic foot muscles and PF. Similar to our results, it was reported that higher

Table 2
Correlation analysis results between ultrasonographic and pedobarographic analysis.

	Thickness of selected tissues				Cross-sectional area			SWV of selected tissues				Age	BMI	Body weight
	PF	AbH	FHB	FDB	AbH	FHB	FDB	PF	AbH	FHB	FDB			
Peak pressure	0.12	−0.05	0.02	0.22	−0.01	0.07	0.37	−0.15	−0.12	−0.09	0.08	0.13	0.22	0.28**
Mean pressure	0.22	−0.10	0.04	0.23	−0.08	0.04	0.32	−0.14	−0.08	−0.08	0.02	0.03	0.21	0.28**
Contact area	0.58*	0.55*	0.52*	0.48*	0.43**	0.52*	0.59*	−0.13	−0.14	−0.03	−0.17	0.05	0.57*	0.67*
Heel maximum force	0.53*	0.38**	0.41**	0.37**	0.47*	0.37**	0.48*	−0.24	−0.13	−0.11	0.01	0.10	0.44**	0.55*
Midfoot maximum force	0.28**	0.03	0.11	0.11	0.08	0.08	0.27	−0.22	−0.06	−0.01	−0.04	0.09	0.31**	0.29**
Metatarsal maximum force	0.08	−0.22	0.11	−0.47*	−0.17	0.13	−0.46**	−0.10	−0.12	−0.05	−0.14	0.04	0.26**	0.28**
Force time integral	0.48*	0.56*	0.46*	0.52*	0.47*	0.52*	0.54*	−0.31**	−0.20	−0.11	−0.19	0.02	0.62**	0.62*
Pressure time integral	0.04	−0.06	0.07	0.11	0.16	0.15	0.08	−0.04	−0.19	−0.08	−0.20	0.22	0.29**	0.29**
Body weight	0.53*	0.42**	0.31**	0.42**	0.56**	0.36**	0.48**	−0.36**	−0.38**	−0.06	−0.07	0.23	0.91**	
Body mass index	0.49*	0.26**	0.35**	0.34**	0.35**	0.30**	0.32**	−0.34**	−0.43**	−0.17	−0.06	0.35*		
Age	0.09	0.14	0.14	0.02	0.14	0.16	0.09	0.07	−0.19	−0.18	0.23			

*p < 0.001, **p < 0.05. Plantar fascia, PF; abductor hallucis, AbH; flexor hallucis brevis, FHB; flexor digitorum brevis, FDB; SWV, Shear-Wave Velocity; BMI, Body mass index.

body mass is related to an increase in plantar maximum force, contact area, and force-time integral [7]. In addition, it has been suggested that higher body mass is related to larger foot muscles and PF [24,25].

Our correlation analysis results suggest that age does not correlate with plantar pressure distribution and ultrasonography results. Similar to our results, it was reported that age is not related to morphology of the intrinsic foot muscle in young or middle-aged individuals [26]. Eby et al. [27] found that muscle stiffness increased with advancing age. On the other hand, Aiter et al. [13] reported that there is a weak negative correlation ($r = -0.24/-0.27$) between age and thickness and cross-sectional area of AbH muscle; however, their study included individuals aged between 20 and 77 years. Furthermore, it was reported that age can affect the parameters in plantar pressure analysis, such as peak pressure or contact area [6]; however, these studies included young, middle aged, and geriatric individuals. In summary, age is a potential parameter which may affect plantar pressure distribution as well as morphology and mechanical properties of muscle. A potential reason for not being able to show a relationship between age and the parameters assessed could be the fact that young individuals with a very short age range were included in the study.

The obtained results suggest that higher body mass and BMI cause higher plantar pressure and force values, and it may cause hypertrophy of the intrinsic foot muscles and PF because of higher loading on the intrinsic foot muscles and PF. It is well known that higher body mass and abnormal plantar pressure and force distribution are related to several foot disorders such as plantar fasciitis or Achilles tendinitis [28,29]. In addition, higher body mass and abnormal plantar pressure and force distribution could cause a muscle damage and/or fatigue [8,9,30] or pathological changes in PF structures [14], which may cause foot pain and/or increase the risk of foot disorders. An approach involving help to provide normal plantar pressure and force distribution such as an orthotic device, and/or losing weight in individuals overweight and obese could decrease the loading on the intrinsic foot muscles and PF. A decrease in loading on the intrinsic foot muscles and PF may decrease the risk of damage in foot muscles and the PF, which may eventually decrease the risk of foot pain and disorders related to these structures.

This study has a few limitations. Firstly, in this study, the relationship between plantar pressure and the PF and intrinsic foot muscles was investigated during static standing position. It may be different during different functional activities such as walking or running. Secondly, the study included only young or middle-age sedentary individuals. In different populations (geriatric, athletes, etc.), the relationship between plantar pressure and the PF and intrinsic foot muscles might be different.

In conclusion, it was found that peak and mean pressure values are not related to thickness, stiffness, and cross-sectional area of PF, AbH,

FHB, and FDB. The results of the study show that larger PF and intrinsic foot muscles are related to higher maximum force, contact area, and foot-time integral. Moreover, the stiffness of these structure does not affect the results of the plantar pressure analysis. In addition, it was found that higher body mass and BMI are related to higher pressure, force, contact area, force-time integral as well as larger intrinsic foot muscles and PF. The results suggest that abnormal force and contact area and higher body mass may cause hypertrophy of the PF and foot intrinsic muscles.

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