

The effects of gait speed on plantar pressure variables in individuals with normal foot posture and flatfoot

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Purpose: It is not known how gait speed affects plantar pressure characteristics in flatfoot. The aim of this work was to investigate the effects of gait speed on plantar pressure variables in flatfoot by comparing it to normal foot posture. *Methods:* Thirty individuals with flatfoot and 30 individuals with normal foot posture were recruited. Plantar pressure variables were obtained by a pressure-sensitive mat at self-selected slow, normal, and fast speeds. All assessments were performed on the dominant foot, and three satisfactory steps were obtained for each gait speed condition. The order of gait speeds was randomized. *Results:* In the flatfoot group, the contact area was higher in the midfoot, third metatarsal, and hallux at all speeds, also in the second metatarsal at slow and normal speeds than the normal foot posture group ($p < 0.05$). The maximum force was higher in the midfoot and hallux at all speeds in the flatfoot group ($p < 0.05$). Also, the maximum force was lower in the first metatarsal at normal and fast speeds, and in the lateral heel at fast speed ($p < 0.05$). In the flatfoot group, the peak pressure was found to be higher in the hallux at slow speed, but to be lower in the first metatarsal at fast speed ($p < 0.05$). Further, plantar pressure distribution was affected by gait speed in both feet. *Conclusions:* Analysis of plantar pressure variables should be performed at different gait speeds.

Key words: gait analysis, gait speed, pes planus, foot posture, plantar pressure analysis

1. Introduction

The foot type is classified as normal, flat (planus), and cavus based on the height of the medial longitudinal arch (MLA) [17]. Flatfoot is defined as a decrease in the height of the MLA or loss of this arch [4], [17]. Flatfoot is associated with numerous lower limb injuries in sports, also altered biomechanical function of the lower limb [14], [22]. It was estimated that 20–30% of the general population have different degrees of flatfoot, and most of them are flexible flatfoot, which is defined as a normal arch during non-weight-bearing or tiptoeing, with a collapsing arch during weight-bearing [4].

Plantar pressure parameters are accepted to be important indicators of the foot function and lower limb

biomechanics. Thus, they are recommended to be assessed in the lower limb musculoskeletal disorders [16]. A recent review has suggested that individuals with flatfoot have higher peak pressure, maximum force, and contact area in the midfoot, central forefoot, and hallux, but these variables are lower in the lateral and medial forefoot [2]. The above-mentioned review has also suggested that there is a need for future studies using validated techniques for classifying foot types and standardized methods for collecting plantar pressure variables. What is more, studies comparing plantar pressure variables between normal foot posture and flatfoot have been performed only at normal gait speed [2]. Most studies have suggested that the gait speed alters plantar pressure variables [9], [19], [21], but it is not known whether plantar pressure variables

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differ between normal foot posture and flatfoot at slow and fast speeds. Also, since studies investigating the effects of gait speed on plantar pressure variables included asymptomatic healthy individuals whose foot posture is not classified, effects of gait speed in flatfoot have not been clarified. In flexible flatfoot, the MLA of the foot collapses in various degrees during weight-bearing [4]. Since the gait speed alters the magnitudes of the forces affecting the plantar surface [23], the changes in gait speed may cause a different amount of collapse. Clarifying the effect of different gait speeds on plantar pressure distribution could provide valuable data regarding why flatfoot causes increased susceptibility to the lower limb injuries.

In the light of this information, the current study was designed to determine the effects of gait speed on plantar pressure variables in individuals with flatfoot by comparing it with individuals with normal foot. We hypothesized that the gait speed may affect plantar pressure variables in both normal foot posture and flatfoot. Also, we hypothesized that there might be differences between two foot postures in plantar pressure variables not only at normal speed but at slow and fast gait speeds.

2. Materials and methods

Participants

Ethical approval for this study was obtained from Dokuz Eylul University Institutional Non-invasive Research Ethics Board (Number: 2019/17-26 – Date: 03.07.2019) and all procedures were conducted according to the Declaration of Helsinki. All participants read and signed the informed consent before their participation.

The inclusion criteria for the flatfoot group were as follows: being between 18 and 40 years of age, having Navicular drop test [NDT] greater than 13 mm [25], having Foot posture index-6 [FPI-6] greater than or equal to 6 [5], having bilateral flexible pes planus. The inclusion criteria for the normal foot posture group were as follows: being between 18 and 40 years of age, having NDT of 5–9 mm [25], having FPI-6 of 0–5 [5]. The exclusion criteria for both groups were as follows: a lack of anatomical integrity of the foot, a history of surgery or trauma in the foot region, having other musculoskeletal or neurological problems which may affect gait performance.

Ninety volunteers aged between 18 and 40 years were screened for eligibility according to the inclusion and exclusion criteria mentioned above. We took the

ratio of controls to cases as 1:1, and cases and controls were matched on gender. Thirty individuals with flexible flatfoot (17 females, 13 males) and 30 individuals with normal foot posture (17 females, 13 males) were recruited into the study (Table 1). The sample size was not calculated before the study, but was determined based on the similar studies comparing the plantar pressure variables between normal and flat feet [3]. To prevent the conceptual and statistical problems related to data pooling of both feet highlighted by Menz, only the dominant foot was assessed, not both feet [13].

Table 1. Demographic and anthropometric characteristics and gait speeds of participants, mean (SD)

	Flatfoot group (n = 30)	Normal Foot group (n = 30)	<i>p</i> ^a
Age [years]	24.4 (2.75)	25.33 (2.8)	0.197
Gender [% of female]	% 56.67	% 56.67	1
Height [cm]	169.37 (9.44)	168.23 (7.92)	0.616
Weight [kg]	65.53 (12.4)	64.6 (12.76)	0.775
BMI [kg/m ²]	22.74 (3.21)	22.69 (3.2)	0.948
NDP	16.44 (3.16)	6.67 (1.85)	<0.001*
FPI-6	7.63 (1.75)	3.67 (1.15)	<0.001*
Slow Spd [m/s]	0.84 (0.12)	0.85 (0.16)	0.662
Normal Spd [m/s]	1.17 (0.13)	1.22 (0.12)	0.074
Fast Spd [m/s]	1.54 (0.17)	1.6 (0.18)	0.251

p^a – independent samples *t*-test, * – *p* < 0.05, SD – standard deviation, BMI – body mass index, NDP – Navicular drop, FPI-6 – Foot Posture Index-6, Spd – Speed.

Procedures

All assessments were applied to the dominant foot during walking at different speeds: self-selected slow, normal, and fast speeds. Plantar pressure data were obtained using the pressure-sensitive mat mounted in the middle of the 6-meter walkway. Also, two wireless timing gates were placed at the start and end of the 6-meter walkway to measure gait speed. The traditional midgait collection method, which was previously recommended as a reliable method, was used to obtain plantar pressure data [1], [12]. The participants were positioned approximately 1 meter behind the starting line to ensure that the timing gates were not triggered early and were asked not to disturb the walking patterns until they passed the second timing gate. The order of the gait speed conditions was randomized, and a one-minute rest was given after each gait speed condition. In the slow speed condition, participants were asked to walk at a slower speed than their preferred speed. In the normal speed condition, participants were asked to walk at their preferred speed. In the fast speed condition, participants were

asked to walk at a faster speed than their preferred speed [6].

Also, in order to prevent targeting, all participants were instructed not to look down at the pressure-sensitive mat but to look at a fixed point far from the mat during walking. All participants were allowed to perform a practice session before data collection to ensure a natural gait pattern. Each practice session lasted until the participant was familiar with the pressure-sensitive mat placed in the middle of the 6-meter walkway. Steps taken without targeting the mat and in the normal walking pattern were considered satisfactory steps, and three satisfactory steps were obtained per each gait speed condition.

Plantar pressure variables

The pressure-sensitive mat (HR Mat, Tekscan, USA) placed in the middle of the 6-meter walkway had 4 force sensors per cm^2 . Data were collected at 60 Hz and were calibrated using participants' body weight prior to data collection. FootMat™ Software for Researchers was used to analyze plantar pressure data. Data were collected for nine foot segments: medial heel (MH), lateral heel (LH), midfoot (MF), metatarsals 1–5 (M1–5), and hallux. For each foot segment, the following data were obtained: contact area [cm^2], maximum force [%BW], and peak pressure [kPa] [15].

Gait speed

Wireless Timing Gates (The TCi System, Brower Timing Systems, USA) provide reliable and high precision speed measurement by sending 1 kHz radio signals to the counter up to 1000 feet. When a person passes through the first timing gate, the timer automatically starts to count. When the person passes through the second timing gate, the timer automatically stops, and the measured time is stored on the device's memory [7]. The gait speed [m/s] was calculated by dividing the 6-meter distance to the time measured by timing gates.

Statistical Analyses

The statistical analysis was performed on the 60 participants using the IBM® SPSS® Statistics 25. Shapiro–Wilk test was used to determine whether the data distributed normally. Parametric tests were used because data showed normal distribution. Descriptive statistics were presented with mean and standard deviation. Independent samples *t*-test was used to determine whether there were significant differences between groups in terms of plantar pressure and gait speed variables.

Repeated-measures of ANOVA with Bonferroni correction was used separately for two groups to determine whether there were significant differences in gait speed values and plantar pressure variables between gait speed conditions. The level of significance was set at $p < 0.05$.

Results

No significant differences were found between groups regarding the demographic characteristics ($p > 0.05$). Both foot posture measures were significantly higher in the flatfoot group ($p < 0.05$). Also, no significant difference was found between groups in terms of slow, normal, and fast gait speeds ($p > 0.05$) (Table 1). However, there were differences in gait speed values between gait speed conditions at the 0.001 significance level in both groups.

Comparison of both groups for plantar pressure variables

In the flatfoot group, the contact area was higher in the MF, M3, and hallux at all speeds, also in the M2 at slow and normal speeds ($p < 0.05$). The contact area in any other regions did not differ between groups ($p > 0.05$) (Table 2).

The maximum force was higher in the MF and hallux at all speeds in the flatfoot group ($p < 0.05$). Also, the maximum force was lower in the M1 at normal and fast speeds, and in the LH at fast speed in the flatfoot group ($p < 0.05$). The maximum force in any other regions did not differ between groups ($p > 0.05$) (Table 3).

In the flatfoot group, the peak pressure was found to be higher in the hallux at slow speed, but to be lower in the M1 at fast speed ($p < 0.05$). The peak pressure in any other regions did not differ between groups ($p > 0.05$) (Table 4).

Effects of gait speed on plantar pressure variables

The contact area differed between gait speeds in the MF and M2 in the flatfoot group, and in the M5 and hallux in the normal foot posture group ($p < 0.05$). The contact area in the MF and M2 was lower at fast speed, compared to slow and normal speeds in the flatfoot group ($p < 0.05$), but there was no significant difference between slow and normal speeds ($p > 0.05$). In the normal foot posture group, the contact area in the M5 was higher at normal speed than fast speed ($p < 0.05$), but there was no significant difference between slow and other speeds ($p > 0.05$). Moreover, the contact area in the hallux was found to be lower at slow speed compared to normal and fast speeds in

the normal foot posture group ($p < 0.05$), but it did not differ between normal and fast speeds ($p > 0.05$) (Table 2).

The maximum force differed between gait speeds in all regions except for M4 and M5 in the flatfoot group, and in all regions except for MF in the normal

Table 2. Contact area values [cm^2] of participants, mean (SD)

	Flatfoot group ($n = 30$)				Normal foot group ($n = 30$)				p^3	p^4	p^5
	slow	normal	fast	p^1	slow	normal	fast	p^2			
MH	12.55 (1.59)	12.29 (1.42)	12.62 (1.58)	0.207	12.31 (1.77)	12.34 (1.69)	12.2 (1.82)	0.812	0.588	0.893	0.345
LH	13.36 (1.93)	12.96 (2.01)	13.05 (1.6)	0.201	12.88 (1.72)	12.83 (1.4)	12.64 (1.78)	0.518	0.318	0.771	0.364
MF	26.21 (7.97)	24.84 (7.72)	23.03 (7.22)	<0.001*	17.32 (7.31)	16.71 (6)	15.31 (5.91)	0.055	<0.001*	<0.001*	<0.001*
1st M	10.99 (2.61)	10.79 (1.91)	10.54 (2.07)	0.342	10.08 (1.61)	10.33 (1.6)	10.17 (1.86)	0.746	0.116	0.317	0.470
2nd M	8.87 (1.98)	8.75 (1.55)	8.28 (1.38)	0.002*	7.69 (1.06)	7.65 (1.06)	7.59 (1.33)	0.822	0.006*	0.002*	0.055
3rd M	1.34 (1.7)	1.42 (1.53)	1.19 (1.58)	0.317	9.42 (1.65)	9.39 (1.61)	9.22 (1.91)	0.539	0.040*	0.014*	0.037*
4th M	9.42 (1.37)	9.48 (1.36)	9.36 (1.35)	0.390	8.89 (1.63)	8.84 (1.6)	8.64 (1.65)	0.234	0.177	0.102	0.071
5th M	6.72 (2.03)	6.17 (2.17)	6.09 (1.74)	0.111	5.96 (1.93)	6.12 (1.71)	5.24 (1.74)	0.008*	0.152	0.930	0.065
Hallux	6.82 (0.97)	7.1 (1.17)	7.18 (1.2)	0.055	5.96 (0.89)	6.4 (0.94)	6.5 (0.81)	<0.001*	0.001*	0.013*	0.014*

p^1 – Repeated measures ANOVA for gait speed effect in flatfoot group, p^2 – Repeated measures ANOVA for gait speed effect in normal foot group, p^3 – Independent samples t -test for comparison of groups at slow speed, p^4 – Independent samples t -test for comparison of groups at normal speed, p^5 – Independent samples t -test for comparison of groups at fast speed, * – $p < 0.05$, MH – Medial heel, LH – Lateral heel, MF – Midfoot, M – Metatarsal, SD – Standard deviation.

Table 3. Maximum force values [% BW] of participants, mean (SD)

	Flatfoot group ($n = 30$)				Normal foot group ($n = 30$)				p^3	p^4	p^5
	slow	normal	fast	p^1	slow	normal	fast	p^2			
MH	39.5 (6.2)	45.72 (6.89)	55.57 (9.07)	<0.001*	41.37 (6.27)	47.82 (8.78)	58.33 (10.37)	<0.001*	0.255	0.307	0.280
LH	36.34 (6.87)	39.47 (6.39)	44.85 (8.42)	<0.001*	39.64 (6.42)	42.61 (7.08)	50.61 (9.52)	<0.001*	0.062	0.077	0.017*
MF	21.59 (9.47)	21.1 (10.08)	17.55 (8.67)	0.001*	15.61 (8.5)	13.01 (5.62)	13.27 (6.45)	0.08	0.014*	<0.001*	0.036*
1st M	19.2 (7.86)	22.23 (7.41)	25.6 (9.28)	<0.001*	21.62 (10.64)	27.2 (10.65)	31.94 (12.08)	<0.001*	0.327	0.049*	0.027*
2nd M	21.4 (4.07)	25.4 (6.17)	25.78 (5.97)	<0.001*	22.04 (4.23)	25.33 (4.7)	27.69 (6.43)	<0.001*	0.553	0.963	0.241
3rd M	27.63 (4.38)	30.81 (5.35)	29.82 (6.34)	0.004*	26.71 (4.97)	29.67 (5.16)	28.99 (6.11)	0.003*	0.452	0.403	0.611
4th M	18.99 (4.89)	20.04 (5.21)	17.95 (4.9)	0.09	20.02 (6.23)	20.19 (5.71)	17.3 (5.84)	0.048*	0.483	0.918	0.648
5th M	9.4 (4.53)	8.68 (4.42)	8.06 (4.1)	0.184	10.95 (7.1)	10.65 (5.95)	8.09 (4.89)	0.039*	0.326	0.151	0.978
Hallux	19.76 (6.62)	24.3 (8.28)	29.79 (7.39)	<0.001*	14.63 (7.24)	19.72 (8.68)	25.6 (8.64)	<0.001*	0.006*	0.041*	0.049*

p^1 – Repeated measures ANOVA for gait speed effect in flatfoot group, p^2 – Repeated measures ANOVA for gait speed effect in normal foot group, p^3 – Independent samples t -test for comparison of groups at slow speed, p^4 – Independent samples t -test for comparison of groups at normal speed, p^5 – Independent samples t -test for comparison of groups at fast speed, * – $p < 0.05$, MH – Medial heel, LH – Lateral heel, MF – Midfoot, M – Metatarsal, SD – Standard deviation.

Table 4. Peak pressure values [kPa] of participants, mean (SD)

	Flatfoot group (n = 30)				Normal Foot group (n = 30)				p^3	p^4	p^5
	slow	normal	fast	p^1	slow	normal	fast	p^2			
MH	364.07 (148.08)	431.83 (155.26)	529.6 (167.11)	<0.001*	352.03 (70.25)	405.93 (93.46)	509.97 (106.27)	<0.001*	0.656	0.437	0.594
LH	303.6 (82.63)	353.27 (88.74)	421.33 (96.82)	<0.001*	315.66 (57.94)	353.93 (59.04)	453.66 (77.96)	<0.001*	0.520	0.973	0.164
MF	113.83 (46.57)	126.6 (55.14)	111.03 (45.92)	0.099	120 (58.8)	107.27 (42.44)	124.55 (44.95)	0.183	0.656	0.133	0.258
1st M	223.93 (112.42)	263.8 (92.13)	306.1 (126.65)	<0.001*	247.48 (133.68)	317.93 (169.96)	399.79 (218.66)	<0.001*	0.466	0.131	0.048*
2nd M	332.5 (89.46)	415.6 (125.51)	434.93 (146.29)	<0.001*	320.55 (78.2)	384.97 (111.155)	430.62 (159.82)	<0.001*	0.588	0.321	0.914
3rd M	363 (106.96)	417.73 (127.68)	413.07 (115)	0.001*	357.93 (95.72)	412.33 (110.11)	431.31 (153.23)	<0.001*	0.849	0.861	0.606
4th M	255.07 (88.96)	28.87 (101.84)	259.23 (103.5)	0.252	282.14 (81.83)	295.83 (84.82)	276 (108.01)	0.492	0.229	0.539	0.545
5th M	202.47 (134.82)	206.77 (127.6)	197.43 (133.68)	0.914	231.1 (166.23)	222.47 (160.31)	198.86 (120.21)	0.567	0.470	0.676	0.969
Hallux	416.43 (154)	464.87 (176.29)	545.6 (170.62)	<0.001*	308.66 (162.93)	384 (179.48)	502.28 (169.93)	<0.001*	0.011*	0.084	0.333

p^1 – Repeated measures ANOVA for gait speed effect in flatfoot group, p^2 – Repeated measures ANOVA for gait speed effect in normal foot group, p^3 – Independent samples *t*-test for comparison of groups at slow speed, p^4 – Independent samples *t*-test for comparison of groups at normal speed, p^5 – Independent samples *t*-test for comparison of groups at fast speed, * – $p < 0.05$, MH – Medial heel, LH – Lateral heel, MF – Midfoot, M – Metatarsal, SD – Standard deviation.

foot posture group ($p < 0.05$). In both groups, the maximum force in the MH and hallux was different for all speeds and was higher at faster speeds ($p < 0.05$). Also, in the normal foot posture group, the maximum force in the LH, M1, and M2 was different for all speeds and was higher at faster speeds ($p < 0.05$). The maximum force in the LH was also higher at fast speed, compared to slow and normal speeds in the flatfoot group ($p < 0.05$), but it did not differ between slow and normal speeds ($p > 0.05$). Also, the maximum force in the M1 was higher at fast speed, compared to slow speed in flatfoot group ($p < 0.05$), but it did not differ between normal and other speeds ($p > 0.05$). In the flatfoot group, the maximum force in the MF was lower at fast speed than slow and normal speeds ($p < 0.05$), but it did not differ between normal and slow speeds ($p > 0.05$). In both groups, the maximum force in the M3 was higher at normal speed than slow speed ($p < 0.05$), but it did not differ between fast and other speeds ($p > 0.05$). Moreover, in the normal foot posture group, the maximum force in the M4 and M5 was higher at normal speed than fast speed ($p < 0.05$), but no difference was found between slow and other speeds ($p > 0.05$) (Table 3).

The peak pressure differed between gait speeds in all regions except for MF, M4, and M5 in both groups ($p < 0.05$). In both groups, the peak pressure in the MH and LH was different for all speeds and was

higher at faster speeds ($p < 0.05$). Also, in both groups, the peak pressure in the M3 was lower at slow speed, compared to normal and fast speeds ($p < 0.05$), but it did not differ between normal and fast speeds ($p > 0.05$). Further, in the normal foot posture group, the peak pressure in the M1, M2, and hallux was different for all speeds and was higher at faster speeds ($p < 0.05$). In the flatfoot group, the peak pressure in the M1, M2 and hallux was lower at slow speed, compared to fast speed ($p < 0.05$). Also, the peak pressure was higher in the M2 at normal speed than slow speed ($p < 0.05$), but it did not differ in the M1 and hallux between these speeds ($p > 0.05$). Besides, the peak pressure was higher in the hallux at fast speed than normal speed ($p < 0.05$), but it did not differ in the M1 and M2 between these speeds ($p > 0.05$) (Table 4).

4. Discussion

In the current study, we aimed to investigate the effects of gait speed on plantar pressure variables in individuals with flatfoot by comparing it with individuals with normal foot posture. Our findings indicated that plantar pressure variables differ between normal foot posture and flatfoot at self-selected normal, slow, and fast speeds. Also, plantar pres-

sure distribution was affected by gait speed in both feet.

Recent review has suggested that although there is some evidence regarding the differences in plantar pressure variables between foot postures, future research that uses validated techniques for classifying foot posture and standardized methods for collecting plantar pressure data is needed [2]. In the current study, we used NDT and FPI-6 to determine whether foot type was flatfoot or normal foot. NDP has been suggested to be a valid indicator of the radiographic arch height indices and a statistically significant predictor of the maximum rear foot pronation during walking [11]. FPI has been suggested to be a valid measure by testing against radiographic images and static and dynamic kinematic data of lower extremity [18], [20]. Inter- and intra-rater reliabilities of these two measures were also found to be good to excellent in the recent studies [5], [25]. Moreover, we used the traditional midgait method to obtain plantar pressure variables. The two-step method has been suggested to be an alternative to the midgait method because it is relatively easy to perform and less time-consuming [1]. Since we assessed plantar pressure variables at different gait speeds, we needed distance for acceleration and deceleration, which was the reason why we preferred the midgait method [1].

To the best of our knowledge, the current study is the first trial comparing plantar pressure variables at different gait speeds between normal foot posture and flatfoot. Most studies have suggested that gait speed alters plantar pressure variables [9], [19], [21]. Unlike related studies, we assessed gait speed in addition to plantar pressure variables to consider the differences caused by gait speed in plantar pressure variables, and we found no statistically significant differences in all three gait speeds between the two groups. Further, there were statistically significant differences in gait speed values between self-selected slow, normal, and fast speed conditions in both groups. On the other hand, while the mid-gait collection method has been reported to be valid and reliable to obtain plantar pressure data [1], [12], it is not a standardized protocol for measurement of gait speed. We chose this protocol because our main goal was not to measure gait speed but to measure plantar pressure parameters at self-selected slow, normal, and fast gait speeds. For the contact area, the regions that differ between groups were almost the same at all three gait speeds, but not for the maximum force and peak pressure. The maximum force in the LH was found to be lower in the flatfoot group only at fast speed, which showed that flatfoot may be insufficient to counteract the pronation moment at fast speed. Such insufficiency at fast speed

may result from increased pronation of the hindfoot during faster walking, which can result in the medialization of the loading pattern [19]. Although the peak pressure at normal speed did not differ in any region, it was lower in the M1 at fast speed and higher in the hallux at slow speed in the flatfoot group. These results are indicative of aberrant hallux and first ray mechanics in flatfoot, which should be considered in the clinical setting. Besides, previous studies reported that the individuals with flatfoot have less maximum force and the peak pressure in the lateral forefoot [2], [3], however, we did not find any significant difference in the lateral forefoot between groups. This inconsistency may be due to the differences in the data collection methods used in the studies. The current study is the only one using the midgait method to obtain plantar pressure variables. It has been suggested that the methods used to collect plantar pressure data are not to be sufficiently correlated to be used interchangeably, and just one method should be used consistently [12].

Gait speed has been suggested to alter plantar pressure distribution in asymptomatic individuals [9], [19], [21], however, the effects of gait speed on plantar pressure variables in different foot postures have not been clarified. The MLA collapses in various degrees during weight-bearing in flexible flatfoot [4]. Since the gait speed alters the magnitudes of the forces affecting the plantar surface [23], we hypothesized that gait speed would affect plantar pressure variables in both normal foot posture and flatfoot. Our results showed that the effects of gait speed on the peak pressure distribution are similar in both groups, suggesting that there is a significant increase in the peak pressure in the heel, medial and middle forefoot, and hallux with increasing gait speed, but not a significant change in the MF and lateral forefoot. The aforementioned result is consistent with previous studies and supports that the increased gait speed causes the medialization of the peak pressure pattern, which should be taken into account by clinicians and researchers in the presence of pain or pathology in the medial part of the foot in both foot types.

Unlike the peak pressure, the regions where the contact area significantly differed between gait speeds were different in the two groups. In the flatfoot group, the contact area in the MF and M2 was lower at fast speed. However, in the normal foot posture group, the contact area in the M5 was lower at fast speed and the contact area in the hallux was lower at slow speed. The suggestion that the MLA structures of the flatfoot are more prone to flexibility [24] can explain the significant change that occurs with the change in gait

speed in the contact area of MF and M1, which are the structures forming the MLA. Besides, the maximum force in the heel, medial and middle forefoot, and hallux was higher at faster speeds in both normal and flat feet. It has been suggested that as the gait speed increases, the amplitude of the ground reaction force increases [23]. Thus, the increased maximum force in the most of foot regions at the faster gait speed is an expected result consistent with the literature. However, the maximum force in the MF was lower at fast speed, which has been associated with the cavus or supinated foot previously [2], [3], in the flatfoot group. Also, the maximum force in the lateral forefoot was lower at fast speed, which has been associated with the flat or pronated foot previously [2], [3], in the normal foot posture group. It has been suggested that increased gait speed causes an increase in the magnitude of the foot eversion [8], [19]. However, Hornestam et al. [8] showed that this effect is reversed in the presence of factors inducing excessive pronation, suggesting that faster gait speed causes more inverted average calcaneal position in the situation of excessive pronation. Inversion, called the movement of the calcaneus around its anteroposterior axis, is the component of the triplanar pronation motion [10]. Flexible flatfoot can be also considered as excessive pronation [4], thus, the above-mentioned result found by Hornestam et al. [8] may explain the difference in the change characteristics of the maximum force between the two groups. However, our suggestion cannot be generalized to rigid flatfoot, since rigid flatfoot may fail to modify the maximum force in the MF according to gait speed.

Limitations

There are several limitations in the current study. The main limitation is that the results of this study cannot be generalized to individuals with an ongoing foot injury. Second, this study did not involve individuals with cavus foot, so the effects of gait speed on plantar pressure variables in all three foot types are still not fully clarified. Third, we did not assess the motions of the MLA, so it is still unknown whether there is difference in the amount of collapse between foot types at different gait speeds. In addition to motions of the MLA, we also did not assess lower extremity kinematics, hence, we cannot make an inference regarding the association between the motions of foot segments and plantar pressure variables. However, although not statistically significant, our results may suggest that there is a potential difference between the two groups in self-selected normal speed. This is because we did not control the gait speed (e.g.,

via a treadmill). We aimed to analyze plantar pressure parameters during overground walking at self-selected speeds because overground walking at self-selected speeds is more closely resemble natural walking condition in daily life. However, although the mid-gait collection method we performed has been reported to be valid and reliable to obtain plantar pressure data, it is not a standardized protocol for measurement of gait speed. Thus, it may be useful to conduct research using standardized methods for measurement of both gait speed values and plantar pressure parameters.

5. Conclusions

The current study brings new evidence that plantar pressure variables differ between individuals with normal foot posture and flatfoot not only at normal speed but at slow and fast speeds. It was confirmed that plantar pressure distribution was affected by gait speed in both feet. Our results show that the values and distributions of the maximum force and peak pressure affecting the plantar surface vary at different gait speeds in both foot postures. Thus, the findings of the current study may be useful in the assessment and interpretation of gait in the clinical setting of different foot pathologies. Also, addressing foot posture classification in the clinical setting of lower limb injuries may provide valuable data.

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