

Plantar Pressure Distribution During Level Walking, and Stair Ascent and Descent in Asymptomatic Flexible Flatfoot

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Abstract

The first purpose was to identify the plantar pressure distributions (peak pressure, pressure integral time, and contact area) during level walking, and stair ascent and descent in asymptomatic flexible flatfoot (AFF). The second purpose was to investigate whether peak pressure data during level walking could be used to predict peak pressure during stair walking by identifying correlations between the peak pressures of level walking and stair walking. Twenty young adult subjects (8 males and 12 females, age 21.0±1.7 years) with AFF were recruited. A distance greater than 10 mm in a navicular drop test was defined as flexible flatfoot. Each subject performed at least 10 steps during level walking, and stair ascent and descent. The plantar pressure distribution was measured in nine foot regions using a pressure measurement system. A two-way repeated analysis of variance was conducted to examine the differences in the three dependent variables with two within-subject factors (activity type and foot region). Linear regression analysis was conducted to predict peak pressure during stair walking using the peak pressure in the metatarsal regions during level walking. Significant interaction effects were observed between activity type and foot region for peak pressure ($F=9.508$, $p<.001$), pressure time integral ($F=5.912$, $p=.003$), and contact area ($F=15.510$, $p<.001$). The regression equations predicting peak pressure during stair walking accounted for variance in the range of 25.7% and 65.8%. The findings indicate that plantar pressures in AFF were influenced by both activity type and foot region. Furthermore the findings suggest that peak pressure data during level walking could be used to predict the peak pressure data during stair walking. These data collected for AFF can be useful for evaluating gait patterns and for predicting pressure data of flexible flatfoot subjects who have difficulty performing activities such as stair walking. Further studies should investigate plantar pressure distribution during various functional activities in symptomatic flexible flatfoot, and consider other predictors for regression analysis.

Key Words: Flatfoot; Level walking; Navicular drop; Plantar pressure; Stair walking.

Introduction

Flatfoot describes a dropped or abnormally low medial longitudinal arch (Kitaoka et al, 1997). Flexible flatfoot is an especially common form of dropped arch (Neumann, 2002). During weight bearing, the heel is in valgus, the medial arch flattens and the forefoot deviates in abduction (Mosca, 2010).

The medial longitudinal arch reappears during non-weight bearing (Neumann, 2002). Asymptomatic flexible flatfoot (AFF) is understood as a physiological variant (Moraleda and Mubarak, 2011). It is not possible to determine whether AFF will become symptomatic or remain asymptomatic throughout the individual's life (Cappello and Song, 1998). Some studies have suggested that individuals with AFF might

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lose flexibility after skeletal maturity, resulting in several deformities and soft tissue injuries [e.g. hallux valgus (Coughlin and Jones, 2007), tibialis posterior dysfunction (Dyal et al, 1997), patellar tendinitis, plantar fasciitis (Willilams et al, 2001), tibialis anterior inflammation (Wallensten and Eriksson, 1984), and patella-femoral joint pain (Franco, 1987)]. These deformities and soft tissue injuries would eventually require more complex surgical interventions (Kelikian et al, 2011; Labovitz, 2006).

Therefore, it is important to provide recommendations for the prevention of AFF (Rodriguez and Volpe, 2010). Analysis of the current dynamic foot function is important for AFF (Hosl et al, 2013). For example, stair walking is a common daily living activities that places a higher demand than level walking on the lower extremities (Costigan et al, 2002; Rao and Carter, 2012). Information regarding the plantar pressure distribution during stair walking would be valuable in reducing results of the complex surgical interventions.

Plantar pressure measurement can be used to describe dynamic function of the foot (Cavanagh et al, 1997), and to analyze loading patterns (Bryant et al, 1999). In the plantar pressure measurements, peak pressure, the pressure time integral, and the contact area are the most commonly analyzed variables (Orlin and McPoil, 2000). The peak pressure represents the highest pressure in the foot during one step (Bus and Waaijman, 2013). The pressure time integral represents the amount of total pressure maintained through a specific region multiplied by the time taken to complete the step of gait (Tsung et al, 2004). The contact area represents the amount of surface contact between the plantar surface of the foot and an insole sensor (Orlin and McPoil, 2013).

Plantar pressure distributions have been examined in flatfoot during static standing and walking. Jonely et al (2011) examined peak pressures in the medial region of the foot during static standing and walking. Walker and Fan (1998) evaluated peak pressures in metatarsal regions during walking.

Ledoux and Hillstrom (2002) investigated peak forces in seven regions of the foot during walking. Rao et al (2011) examined peak pressures in three regions of the foot during walking. Teyhen et al (2011) assessed peak pressure, contact area, maximum force, and force time integral in 10 regions of the foot during walking. Sánchez-Rodríguez et al (2012) studied peak pressure in 10 regions of the foot during walking, and Hong (2012) examined peak pressure and the center of pressure trajectory in the medial forefoot and the lateral forefoot during one leg standing.

However, plantar pressure distribution during stair walking has not been established for AFF. For normal feet, only a few studies have examined plantar pressure distributions during stair walking (Lundeun et al, 1994; Maluf et al, 2004). Therefore, the first purpose of this study was to identify level walking, stair ascent and descent influence the plantar pressure distributions (peak pressure, pressure integral time, and contact area) in AFF. The second purpose was to investigate whether peak pressure data during level walking could be used to predict peak pressure during stair walking by identifying correlations between the peak pressures. The research hypotheses were that interaction effects would be observed between the activity and the region of the foot for the three dependent variables (peak pressure, pressure integral time, and contact area), and moderate to strong correlations would be observed between the peak pressure data during level walking and stair walking.

Methods

Subjects

Twenty young subjects (8 males and 12 females) with AFF were recruited to this study (Table 1). The inclusion criteria were: (1) more than 10 mm discrepancy in a navicular drop test (Cote et al, 2005), (2) lower than 5 mm discrepancy in the leg length (Hong et al, 2012), and (3) normal joint range of

Table 1. General characteristics of subjects

(N=20)

Parameters	Mean±SD ^b
Age (year)	21.0±1.7
Height (cm)	167.2±9.8
Weight (kg)	57.9±10.0
BMI ^a (kg/m ²)	20.5±1.6
Foot size (mm)	249.5±18.2
Navicular drop (mm)	15.9±2

^abody mass index, ^bmean±standard deviation.

motion, and normal muscle strength of lower extremity (Hong et al, 2012). The exclusion criteria were: (1) persistent pain of lower extremity within the past six months (Hong et al, 2012), (2) orthopedic maladies that would prevent a normal stance, (Ledoux and Hillstrom, 2002), and (3) a history of lower extremity surgery (Hong et al, 2012). All the subjects signed an informed consent form.

Instrumentation

Navicular Drop Test

The Navicular drop test was used to measure the mobility of the medial longitudinal arch, and to quantify the amount of vertical navicular excursion between neutral subtalar joint positions and relaxed bilateral standing positions (Brody, 1982). The most prominent aspect of the navicular tuberosity was marked with a dot. The first placement was marked on an index ruler at the dot level of the navicular tuberosity when the subject maintained the subtalar joint in a neutral position while sitting. The examiner aligned the index ruler perpendicular to the medial side of the foot. The subtalar joint was deemed to be in a neutral position when the talar head was located equally between the examiner's thumb and index finger. The second placement was marked on the ruler when the subject maintained both feet bearing equal weight while standing. The distance between the two placements on the ruler showed the amount of navicular tuberosity drop from the neutral subtalar joint position to the standing position. A

distance value greater than 10 mm was considered as the flatfoot (Cote et al, 2005). Prior to the navicular drop test, to minimize measurement error, the examiner participated in 10 hours of hands-on training on the test protocol. The training provided instruction on the marked placements, the joint positions of the foot, and the hand positions required (Brody, 1982). The intrarater test-retest reliability of the navicular drop test was determined using an intraclass correlation coefficient [ICC (3,1)] model (Portney and Watkins, 2009) and standard error of measurement (SEM). The intrarater test-retest reliability for the navicular drop test was .88 and SEM was .83 in this study.

Pressure Measurements

The measuring system was a Tekscan insole pressure system (F-Scan Versa System, Tekscan Inc., MA, USA). The Tekscan system uses a thin two-layer (.18 mm) insole sensor containing 960 individual sensors. This system is useful for comparisons of plantar pressure distributions under constant conditions (Kong and De Heer, 2009). The pressure data were analyzed using F-Scan Research ver. 6.70 software (F-Scan Versa System, Tekscan Inc., MA, USA). A dominant foot from each subject was analyzed to satisfy the assumption of independence (Menz et al, 2004). The dominant foot was defined by asking the subjects which foot would be used to kick a ball (Bohannon et al, 1984). The software automatically divided the foot into nine regions [hallux (H), first to fifth metatarsal heads (M1 to M5), mid

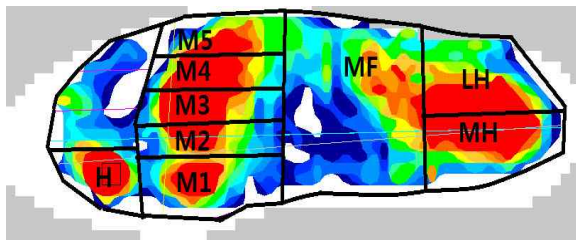


Figure 1. Nine foot regions (H: hallux, M1: first metatarsal head, M2: second metatarsal head, M3: third metatarsal head, M4: fourth metatarsal head, M5: fifth metatarsal head, MF: mid foot, MH: medial heel, LH: lateral heel).

foot (MF), medial heel (MH), and lateral heel (LH)] (Figure 1). The division was realized to assure a high level of precision. Three dependent variables (peak pressure, pressure time integral, and contact area) were calculated in these nine regions. For each of the three activities (level walking, stair ascent, and descent), a minimum of 10 steps was analyzed at a sampling rate of 50 Hz (Jonely, 2011). The initial, final, and mid steps at the turning point were removed to avoid acceleration and deceleration effects, which could influence the results (Bacarin et al, 2009).

Procedures

The examiner performed the navicular drop test. The Tekscan insole sensors were trimmed to the subject's foot size and inserted into standard flat floor shoes provided by the examiner. The insole sensor connector was inserted into cuffs attached to ankle bands. The subjects placed the ankle bands around their ankles and were equipped with a waist belt with a wireless data-logger unit. When the Tekscan system was in place, the examiner explained the experimental procedures to the subjects. Prior to the experiment, the subjects performed a procedure to familiarize themselves with the device for approximately five minutes (Bacarin et al, 2009). Each insole sensor was calibrated using a walk calibration procedure and set to zero prior to each activity as recommended by the Tekscan system guideline. The first activity was 20 m level walking, and the second activity was stair ascent (stair



Figure 2. Stair walking (A: ascent, B: descent).

height: 17 cm, depth: 30 cm, width: 217 cm, 12 steps) (Figure 2-A). The last activity was a stair descent (Figure 2-B). Each of these activities was performed at a self-selected speed for a habitual walking. The subjects were not permitted to use the handrails during these activities.

Statistical analysis

A two-way repeated analysis of variance (ANOVA) was conducted to examine the differences in the three dependent variables with two within subject factors (activity type and foot region). If a significant activity type by foot region interaction effect was found, then one-way ANOVAs were conducted to assess simple effects of activity at each of the nine foot regions. An assessment of the assumptions of the repeated ANOVA was conducted. Greenhouse and Geissers method was used to correct departures from sphericity. Post hoc analyses were conducted to determine pair-wise differences using Bonferroni corrections at a significance level of .017 and a 95% confidence interval. A linear regression was conducted to predict peak pressures during the stair ascent and descent by using the peak pressure in metatarsal regions during level walking. The level

of significance was set at $\alpha=0.05$. Statistical analysis was performed using SPSS ver. 20.0 software (IBM Inc., Somers, NY, USA). All the data are expressed as the mean and standard deviation.

Results

Interaction effect

A significant interaction effect between the activity and the foot region was observed for peak pressure ($F=9.508$, $p<.001$) (Table 2). A significant simple effect of activity was found at the H ($F=4.963$, $p=.012$), M2 ($F=21.083$, $p<.001$), M3 ($F=26.504$, $p<.001$), M4 ($F=5.822$, $p=.006$), MH ($F=52.388$, $p<.001$), and LH ($F=33.177$, $p<.001$) regions. Peak pressures were significantly greater during level walking than during the both stair ascent and descent in the M3, M4, MH, and LH regions. The peak pressure of H was greater during level walking than during the stair ascent, and the peak pressure of M2 was greater

during level walking than during the stair descent.

A significant interaction effect between the activity and the foot region was observed for the pressure time integral ($F=5.912$, $p=.003$) (Table 2). To assess the simple effects of activity by foot regions. A significant simple effect of activity was found at the M1 ($F=5.134$, $p=.011$), MH ($F=28.620$, $p<.001$), and LH ($F=17.366$, $p<.001$). The pressure time integrals were significantly greater during both level walking and the stair ascent than during the stair descent in the MH and LH regions. The pressure time integral of M1 was greater during the stair descent than during level walking.

A significant interaction effect between the activity and foot region was observed for the contact area ($F=15.510$, $p<.001$) (Table 2). To assess the simple effects of the activity by foot regions. A significant simple effect of activity was found at the H ($F=13.162$, $p<.001$), M1 ($F=7.780$, $p=.003$), M2 ($F=6.398$, $p=.010$), MF ($F=8.208$, $p=.004$), MH ($F=17.156$, $p<.001$), and LH ($F=35.996$, $p<.001$)

Table 2. Plantar pressure distribution in the nine foot regions (N=20)

Variable	Activity	H ^a	M1 ^b	M2 ^c	M3 ^d	M4 ^e	M5 ^f	MF ^g	MH ^h	LH ⁱ
Peak pressure (kPa)	Level	299.2	187.3	240.2	275.2	195.5	135.0	78.8	230.1	207.8
	waking	(144.8) ^j	(98.4)	(71.0)	(92.52)	(80.6)	(55.8)	(27.3)	(89.2)	(77.9)
	Stair ascent	213.7 (97.2) [†]	191.5 (91.44)	225.2 (97.9) [‡]	236.1 (94.3) ^{†,‡}	160.4 (49.5) [†]	128.3 (65.4)	70.6 (24.0)	136.2 (69.5) ^{†,‡}	126.0 (100.0) [†]
	Stair descent	260.1 (155.0)	184.7 (108.4)	160.4 (65.8) ^{†,‡}	182.5 (59.6) ^{†,‡}	159.9 (60.0) [†]	116.6 (51.2)	79.9 (19.9)	93.8 (49.3) ^{†,‡}	84.6 (48.83) [†]
Pressure time integral (kPa×s)	Level	31.9	28.1	37.4	42.2	34.8	29.5	17.6	30.3	29.2
	waking	(16.0)	(9.5)	(13.9)	(16.3)	(12.9)	(10.2)	(7.0)	(12.9)	(19.5)
	Stair ascent	32.7 (24.1)	37.9 (20.9)	50.6 (40.5)	49.5 (29.6)	39.2 (20.3)	31.9 (11.9)	20.4 (5.3)	29.6 (13.0) [‡]	27.3 (15.3) [‡]
	Stair descent	45.3 (25.8)	40.5 (14.0) [†]	46.6 (19.6)	49.8 (18.2)	43.7 (13.2)	33.4 (11.5)	18.9 (6.2)	17.7 (11.2) ^{†,‡}	17.8 (11.6) ^{†,‡}
Contact area (cm ²)	Level	5.6	10.4	7.3	8.3	8.1	7.3	18.6	15.3	14.5
	waking	(1.6)	(2.0)	(1.5)	(1.5)	(1.4)	(1.6)	(10.5)	(2.0)	(1.9)
	Stair ascent	5.1 (1.6) [†]	10.8 (2.4)	7.5 (1.4) [‡]	8.2 (1.5)	7.9 (1.5)	7.1 (1.8)	20.5 (11.3) [†]	14.6 (1.7) [‡]	12.2 (2.7) ^{†,‡}
	Stair descent	4.8 (1.8) [†]	11.4 (2.4) [†]	7.8 (1.5) ^{†,‡}	8.2 (1.4)	7.8 (1.2)	7.4 (1.4)	22.6 (11.3) [†]	12.2 (3.1) ^{†,‡}	9.9 (4.1) ^{†,‡}

^ahallux, ^bfirst metatarsal head, ^csecond metatarsal head, ^dthird metatarsal head, ^efourth metatarsal head, ^ffifth metatarsal head, ^gmid foot, ^hmedial heel, ⁱlateral heel, ^jstandard deviation, [†]significance differences compared to level walking, [‡]significance differences between stair ascent and descent.

regions. The contact areas were significantly greater during level walking than during either the stair ascent or descent in the H, MF, and LH regions. The contact area of MH was greater during level walking than during the stair descent, whereas the contact areas of M1 and M2 were greater during the stair descent than during level walking.

Linear relationship

A significant linear relationship between the peak pressure data during level walking and during stair walking was observed. Based on the data, the peak pressure in the five metatarsal regions during the stair ascent and descent was predicted from the data during level walking, except for M5. The regression equations predicting peak pressure during the stair ascent and descent accounted for variance in the range of 25.7% and 65.8% (Table 3).

Discussion

The first purpose of this study was to identify the plantar pressure distributions during level walking,

stair ascent, and descent in AFF. Our results demonstrate that activities in the foot region influence the peak pressure. Our results correspond with those of previous studies, which reported that flatfoot exhibits hallucal loading patterns during level walking. The previous studies reported that flatfoot had the highest pressure in H during level walking (Jonely, 2011; Ledoux and Hillstrom, 2002; Rao, 2011). The highest peak pressure data could be explained by flatfoot hypermobility. Ledoux and Hillstrom (2002) reported that foot mobility, especially vertical navicular mobility in flatfoot, induces the high pressure. In another study, Rao et al (2011) reported that a low arch has more metatarsophalangeal joint flexibility than a normal arch and induces higher pressures in H. In accordance with these studies, our study showed that H had the highest peak pressure during level walking. However, the overall patterns of peak pressure are in close agreement with those reported for normal feet in a previous studies (Rao and Carter, 2012; Wervey et al, 1997). These similar patterns might be due to muscular compensation in AFF. Previous studies suggested that the medial longitudinal arch in AFF is supplemented by com-

Table 3. Prediction of peak pressure data in the five metatarsal regions during stair ascent and descent from data during level walking (N=20)

Independent variable	Dependent variable	b	Constant	R ²	Adjusted R ²	p
Level M1 ^a	Ascent M1	.639	71.822	.472	.443	.001*
	Descent M1	.887	18.522	.648	.629	<.001*
Level M2 ^b	Ascent M2	.979	-9.948	.504	.476	<.001*
	Descent M2	.632	8.631	.464	.434	.001*
Level M3 ^c	Ascent M3	.704	31.474	.443	.412	.001*
	Descent M3	.470	53.000	.534	.508	<.001*
Level M4 ^d	Ascent M4	.505	61.656	.676	.658	<.001*
	Descent M4	.499	62.234	.450	.419	.001*
Level M5 ^e	Ascent M5	.638	42.227	.296	.257	.013*
	Descent M5	.295	76.744	.104	.054	.166

^afirst metatarsal head, ^bsecond metatarsal head, ^cthird metatarsal head, ^dfourth metatarsal head, ^efifth metatarsal head, *significant findings.

pensations by extrinsic muscles, such as the tibialis anterior and peroneus longus (Gray and Basmajian, 1968; Ledoux and Hillstrom, 2002).

The pressure time integral data of our study were influenced by activities in MH and LH. A previous study reported that the pressure time integral data was increased in H, M1 to M5, and MF during stair walking more than level walking in subjects with normal feet (Rao and Carter, 2012). However, in the present study, the total demands applied to H, M1 to M5, and MF were similar among the activities in the subjects with AFF. Instead, the pressure time integrals of MH and LH during the stair descent were reduced significantly more than those during level walking and the stair ascent. The results may be related to the contact pattern of the forefoot including H and M1 to M5, with the forefoot steps occurring first. During the stair walking, the forefoot contact pattern dominated the stance phase more than heel initial contact pattern (McFadyen and Winter, 1988). This suggests that a decrease in the heel contact time could contribute to a decreased pressure time integral in MH and LH.

The activities of the foot region were influenced by the contact area in the current study. Previous studies reported that the contact areas in medial parts of foot were increased in flatfoot compared with a normal foot (Ledoux and Hillstrom, 2002; Sneyers et al, 1995). In accordance with previous studies, our results indicate that the contact area of M1 and M2 increased significantly during the stair ascent and descent and that the contact area of MF increased more than during level walking. In addition, they suggest that the contact area of H was reduced during the stair ascent and descent. These findings could be associated with excessive pronation in flexible flatfoot. Pronation is comprised of forefoot abduction, dorsiflexion, and heel eversion. The hypermobility of flexible flatfoot and the more demanding nature of stair walking compared with level walking could induce excessive pronation of the foot (Snook, 2001; Wervej et al, 1997). This could increase the

contact area of the medial part of the foot. In our study, the contact area data of MH and LH significantly decreased during the stair ascent and descent more than level walking. This decrease in MH and LH is in agreement with the pressure time integral data. It may be related to the forefoot contact pattern during stair walking, with a larger area of the metatarsal region inducing a lower contact area of the heel.

The second purpose of this study was to investigate whether peak pressure data during level walking could be used to predict peak pressure during stair walking. Our result shows strong to moderate correlations between the peak pressure in M1-M4 during level walking and stair walking. The prediction data of this study indicates that metatarsal regions show a similar pattern during three activities. In a previous study of subject with normal feet, correlation coefficients ranged between 37% and 70% (Rao and Carter, 2012). The correlation coefficients in the current study (between 25.7% and 65.8%) are lower than those of the previous study. The differences may be related to the hypermobility of flexible flatfoot. As a result of this hypermobility of flexible flatfoot, the activities may induce navicular drop. The differences in the level of navicular drop between individuals make it difficult to predict the peak pressure of flatfoot than normal feet. Nevertheless, the model of our study could be useful for evaluating gait patterns and for predicting pressure data of symptomatic flexible flatfoot subjects who have difficulty performing activities such as stair walking. Moreover, the plantar pressure distribution in AFF suggested in this study can be used to analyze gait patterns and to prevent symptoms that could be induced in the future by corrections of the gait patterns.

Some limitations of this study need be considered for future studies. First, this study included only activities of level walking and stair walking. Further studies of flatfoot should include other functional activities such as jumping, running, and hill climbing.

We used only peak pressure data as a predictor for explaining the differences in the peak pressure between level walking and stair walking. Considering other predictors that may include gender, amount of navicular drop, and symptom are needed in the future.

Conclusion

The first purpose of our study was to determine the plantar pressure distributions during level walking and stair walking in subjects with asymptomatic flatfoot. We conclude that the plantar pressure distributions in asymptomatic flexible flatfoot are different between level walking and stair walking. The second purpose of our study was to determine whether peak pressure data during level walking could predict peak pressure data during stair walking. The regression results suggest that peak pressure data during level walking could be used to predict peak pressure data during stair walking. We believe that these findings can be used to evaluate gait patterns of asymptomatic flexible flatfoot. Moreover, they can be used to predict gait patterns in subjects with symptomatic flexible flatfoot who have difficulty performing functional activities because of pain. Further studies are recommended to investigate the plantar pressure distribution during other functional activities, add other predictors to the regression analysis, and include subjects with symptomatic flexible flatfoot.

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