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THE EFFECTS OF CHANGES IN STEP WIDTH ON PLANTAR FOOT PRESSURE PATTERNS OF YOUNG FEMALE SUBJECTS DURING WALKING

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The aim of this study was to investigate the foot plantar pressure distribution and the effect of different step width during walking. Methods: Nineteen female volunteers who aged 18∼30 years old and with no history of lower extremity injury were considered. Subjects walked at a pre-determined set speed with varied step width (5 cm, 10 cm, and 20 cm) for three trials at each step width. This study used an in-sole plantar pressure measurement system to collect the peak pressure, maximum ground reaction force, pressure–time integral, and force–time integral data of eight different foot regions. Results: The data revealed that the peak plantar foot pressure on the medial arch increased with wider step width ($p < 0.05$). In contrast, maximum ground reaction force, peak plantar pressure, pressure–time integral, and force–time integral on the lateral arch and lateral side of the metatarsals decreased with wider step width ($p < 0.05$). Conclusion: The results of this study revealed that smaller step width during walking result in decreasing the pressure on the medial arch of the foot. It may have the relieving effect for clients with pes planus and it can be a reference for rehabilitation clinicians while treating the above-mentioned subjects.

Keywords: Walking; gait; step width; plantar foot pressure.

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1. Introduction

Walking is a daily fundamental movement and it is frequently chosen as an exercise program for people to improve or maintain health. However, a prolonged improper walking pattern could have detrimental effects on the lower extremity especially at foot. Foot is the main part of interaction of the body with the walking surface during locomotion through its role as supporting the body weight and as a rigid lever at push-off.[1] Therefore, it is important to have a thorough understanding of the extrinsic and intrinsic factors affecting walking pattern, especially the consequence with the gait pattern changed habitually.

Normal locomotion is consisted of the periodic movement of each foot and heel-to-toe gait. As the foot progresses, loading of the foot is continued and the weight acceptance is experienced from the heel to the hallux.[1] The impulse while foot contact with the ground which should be absorbed by the lateral arch is now absorbed by the medial arch make the shock absorption effect less effective. In the long run, the mechanism for shock absorption can be damaged. People with flat foot and lower medial foot arch possibly have a worse buffering effect in wider step walking. In asymptomatic subjects, greater step-width walking may activate tibia posterior to maintain the arch stability, it is not only a problem of muscle fatigue but also a problem of foot deformity.

It was found recently that the study of human walking is essential to prevent and predict functional disability in the elderly. Recently, some researchers have emphasized on the gait function and locomotion variables in the elderly, and the influence of interventions on human walking. Many exercise programs were used to improve both balance and gait function during level walking in the elderly, including gait exercise,[2] functional walking,[3] balance exercises,[2,3] etc. Nordin *et al.* have shown that an alternation in mean step width is related to the risk of future falling during performing a subtraction task.[4] However, previous studies focused almost entirely on physical functional tests and gait characteristics to assess gait functions. Only a few authors investigated the plantar pressure while walking at different step width. Gait pathology often affects plantar pressure,[4] so the measurement of plantar pressures is important to determine whether differences in loading pattern of the plantar aspect of the foot throughout the locomotion between pathological and normal gait result from alternations in lower extremity.

Pes planus, known as flat foot, is a condition where the arch of the foot is absent and calcaneus has eversion. Previous literature showed that the ground reaction force (GRF) is increased in the medial of the foot for subjects with pes planus.[5] In addition, foot deformities have been associated with alternations plantar vertical GRF and loading pattern on plantar aspect of the foot such as plantar pressures.[4,6] Ledoux *et al.* have determined the distributed vertical GRF between subjects with normal foot and with pes planus. They found that flat foot have significantly more vertical GRF at sub-hallucal area and there were no difference seen under the other area.[7] In order to decrease excessive foot pronation, some researchers used low-Dye taping to support longitudinal and transverse arch. Lange *et al.*[8] found mean and peak pressure significantly increased under the lateral midfoot and under the toe, and decrease under the heel and forefoot after using low-Dye taping in subjects with navicular drop in excess of 10 mm. Russo and Chipchase[9] also demonstrated low-Dye taping significantly altered and decreased peak plantar pressure under the medial midfoot in subject with normal foot presence.

Hiroyuki *et al.*[2] have contended that gait reeducation can improve dynamic balance and gait functions in the frail elderly. Furthermore, the specific effects of balance and gait functions have evaluated among frail elderly individuals with interventions of gait exercise consisting of 10 min of continuous walking, 5 min of tandem walking, and 5 min of walking sideways. Additionally, Faber *et al.*[3] indicated that functional walking and balance exercises have positive effects on falling and physical performance in pre-frail elderly. In this study, functional walking was consisted of 10 exercises which emphasis on balance, mobility, and transfer training.[3] Walking is good for elders and it is greatly engaged into the clinical treatment for subjects with respiratory disease, cardiac disease, and joint dysfunction. However, long-time improper walking can be an accumulating workload to feet and may induce ulcer and fatigue-related foot problems.[5,6,10–12] Despite the frequent use of plantar pressure measurements in research, the effect of walking with different step width on peak plantar pressure at specific plantar regions in normal adults has not been clearly defined.

Gait cycle means when it begins one foot strikes the walking surface and ends when it strikes the walking surface again.[7] The gait cycle can use temporal gait measurements to demonstrate its characteristic. Normal gait is consisted of five components including stability in stance, sufficient foot clearance during swing, appropriate swing phase pre-positioning of the foot, an adequate step length, and energy conservation.[7] The pathological gait has lost one of the above-mentioned five components for normal gait. Temporal parameters play the important role especially in stability in stance during normal gait.[7] Previous studies showed stride time, stride length, step width, and double support time have been related to the stability.[13,14] Step width is not only the mediolateral distance between the medial malleoli during the period of double support but also a common task for the evaluation of dynamic balance, such as tandem walk.[15] The displacement of body could project onto three planes of space including lateral displacement in a horizontal plane and vertical displacement in frontal plane and combined displacement of lateral and vertical, which are responsible for trunk stability during the stance phase. Lateral displacement of body and foot is controlled by the hip abductors and adductors in the swing phase of cycle. Previous studies show that the lateral displacement can be increased with the feet more widely separated while human walking and decreased while the feet close to the progression line in level walking.[7] It is the important issue to investigate step width control, stability in stance, and falls relationships.[16] The control of step width is one of the highlights, potential values to predict the risk for falls to the side. Krebs *et al.* have examined the difference of step width between subjects with vestibulopathy and normal subjects. They found vestibulopathy subjects chose a similar step width with normal one, but at the cost of slower gait.[17]

Walking is a daily fundamental movement and is frequently chosen as exercise program for people to improve or maintain health. Therefore, it is important to have a thorough understanding of the extrinsic and intrinsic factors affecting walking as well as the consequence of change in the gait pattern, such as increased step width walking for increasing stability purpose or habitual reason. In the present study, we examined the initial influence on the plantar pressure pattern during different step width walking. The plantar pressure values can be used to modify a management program in the elderly through alterations in the gait exercises. We propose to study the effects of changes in step width on plantar foot pressure patterns during walking in young female subjects. Specifically, we hypothesized that there are no difference in the plantar pressure with wider or narrower step width walking in young female subjects.

2. Methods

2.1. *Subjects*

Nineteen healthy female volunteers (age 24.2 ± 5.8 years, height 160.1 ± 5.4 cm; weight 53.2 ± 5.6) with no previous foot injury were recruited for the study. Subjects were excluded if they had a history of lower extremity injuries, neurological disorders, and any serious lower extremity musculoskeletal disorders. According to the Kaohsiung Medical University Hospital of research ethics committee, all subjects had to write consent following verbal and written explanation of the project. All subjects agreed to the consent and were studied.

2.2. *Experimental design and procedure*

Subjects walked at the speed of 96 steps/min with different step width of 5 cm, 10 cm, and 20 cm. Step width is the mediolateral distance between the medial malleoli during the period of double support. The walking tasks at 96 steps/min performed with cadence-controlled in all subject. A 96 steps/min cadence was chosen in accordance with previous studies and pilot studies.[18] According to the study of Owings *et al.*, the mean step width is 10 cm for subjects including 18 young adults and 12 healthy older adults. In this study 10 cm was chosen as normal step width. For walking tasks, the subjects were first asked to perform level walking with 96 beats/min by a metronome setting. There were three different selected step widths including narrow (5 cm), regular (10 cm), and wide (20 cm).[19] After two practice trials, the data from three trials were collected in different step widths to calculate the mean value. Six steps were collected per straight line walk at each trial. The subjects were fit with PEDAR insoles (Novel gmbh, Munich, Germany) and a standardized shoe (JU, JUMP, Taiwan) during the experimental protocol. The shoe sizes ranged from women's size 23 to 24.5 (Japanese Industrial Standard for shoe size). The JUMP shoes were purchased solely for Pedar data analysis and had not been used for any other purposes.

The Pedar insole system (Pedar-x, Novel Inc, Munich, Germany) uses a matrix of multiple capacitance transducers. The insoles consist of 99 capacitive pressure sensors. The sampling rate of insoles is set at 50 Hz. Each insole is connected to a PC via BluetoothTM wireless. The measurement data is collected in the PC and analyzed by the Novel-Win Masks software (Novel USA, Inc, Minneapolis, MN). The data collected were divided into eight regions or masks using the Novel Win Mask software system. Analysis software is used to average the measurements and calculate peak pressures, maximum force, force–time integrals, and pressure–time integrals in eight different regions of the foot: toes, hallux, lateral, central, and medial forefoot region, medial and lateral midfoot and heel. (Fig. 1) The region of heel comprised the first 0% to 30% of foot length, the midfoot the next 30% to 60%, the forefoot the following 60% to 85%, and the hallux/toe the remaining 85% to 100%. The midfoot region width was divided into two equal parts. The forefoot region width was divided into equal thirds, creating three forefoot regions. The hallux/toe region width was also divided into two parts, with the hallux region occupying the medial 40% and the toe region occupying the lateral 60%.[20]

The peak pressure represents the highest pressure value measured by each sensor over the entire walking tasks. The magnitude of pressure was calculated from the measured force by the area of the insole while subjects performing level walking. This indicated the maximum value of the measured pressures for different sensors in a specific foot region. As this measure is not affected by the size of each region, the peak pressure can be used to characterize the loading variation between the different feet masks.[21] The maximum force represents the highest force value acted on each sensor in the in-sole while subjects performing level walking.[22] Due to

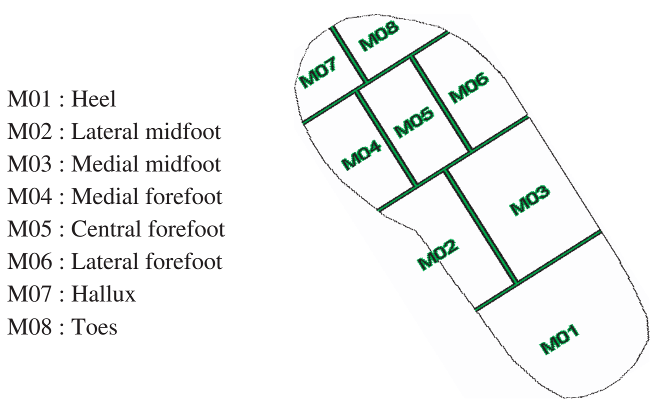

Fig. 1. Eight anatomically defined regions of the foot used for plantar pressure pattern analysis.

variations in each plantar region, comparison of the maximum force is not possible between regions. However, maximum force could be used to compare loading between variations in the walking base. The integrals or impulse of the pressure–time and force–time are determined by the area beneath the pressure–time curve and the force–time curve. Area refers to the amount of surface contact between the surface of the plantar aspect of foot and the sensor.

2.3. *Data analysis*

Mean and standard deviation were calculated from each of variables from foot pressure distribution in three different step-width walking condition as shown in Tables 1–4. A repeated-measures ANOVA was used to determine if there was a significant interaction in relation to changes in foot plantar pressure variables during three different step width during level walking. Tukey's post hoc analyzes were used to examine if there is any difference between each pair of different step width. Significant level was set up as $\alpha < 0.05$ for all two-tailed tests.

3. Results

The maximum plantar pressure of both lateral (MO3) and medial arch (MO2) has a significant difference ($p < 0.05$). With step width of 5 cm, 10 cm, and 20 cm, the

Table 1. The peak pressure at different step width (Unit: Kpa).

Mask[a]	5 cm	10 cm	20 cm	F	Post Hoc
MO1	193.1 (57.1)	192.3 (52.1)	196.0 (49.0)	0.25	
MO2	72.8 (31.4)	83.9 (36.4)	91.2 (45.3)	4.26[b]	W20 > W10 > W5[c]
MO3	117.9 (51.2)	105.1 (33.9)	94.0 (31.1)	4.9[b]	W5 > W10 > W20
MO4	224.1 (86.1)	228.9 (80.2)	259.0 (93.9)	2.34	
MO5	182.0 (46.1)	189.2 (45.3)	185.5 (64.7)	0.23	
MO6	160.4 (54.9)	149.1 (49.6)	140.8 (38.5)	2.44	
MO7	217.9 (110.2)	216.1 (109.3)	244.5 (104.7)	1.77	
MO8	108.0 (52.1)	100.1 (53.7)	103.7 (50.4)	2.47	

[a]MO1: Heel, MO2: Lateral midfoot, MO3: Medial midfoot, MO4: Medial forefoot, MO5: Central forefoot, MO6: Lateral forefoot, MO7: Hallux, MO8: Toes.
[b]$*p < 0.05$, $**p < 0.01$.
[c]W: Step width.

Table 2. The maximum force at different step width (Unit: N).

Mask[a]	5 cm	10 cm	20 cm	F	Post Hoc
MO1	371.7 (136.8)	374.7 (105.1)	381.9 (107.2)	1.29	
MO2	17.2 (16.6)	18.7 (17.2)	19.1 (17.9)	0.83	
MO3	108.2 (59.7)	87.0 (55.5)	80.3 (48.3)	4.57[b]	W5> W10> W20[c]
MO4	144.2 (61.7)	156.7 (68.1)	174.8 (87.1)	1.97	
MO5	146.2 (43.8)	150.0 (42.6)	149.1 (47.9)	1.10	
MO6	107.8 (47.8)	95.8 (44.1)	83.0 (39.0)	6.51[b]	W5> W10> W20
MO7	71.4 (36.6)	71.3 (38.7)	81.3 (33.5)	2.75[b]	
MO8	37.0 (24.6)	35.7 (28.0)	36.6 (26.3)	1.96	

[a]MO1: Heel, MO2: Lateral midfoot, MO3: Medial midfoot, MO4: Medial forefoot, MO5: Central forefoot, MO6: Lateral forefoot, MO7: Hallux, MO8: Toes.
[b]$*p < 0.05$, $**p < 0.01$.
[c]W: Step width.

Table 3. The force–time integral at different step width (Unit: Ns).

Mask[a]	5	10	20	F	Post Hoc
MO1	107.5 (39.2)	111.6 (34.9)	111.2 (45.4)	0.20	
MO2	4.0 (4.3)	3.7 (3.0)	4.3 (3.9)	0.37	
MO3	32.6 (22.6)	25.3 (17.8)	22.8 (18.0)	4.00[b]	W5 > W10 > W20[c]
MO4	41.1 (22.7)	40.8 (22.7)	49.7 (25.7)	2.12	
MO5	39.3 (13.4)	38.9 (12.7)	41.0 (15.2)	0.59	
MO6	30.1 (15.2)	24.2 (12.2)	23.2 (13.8)	4.55[b]	
MO7	17.5 (11.2)	15.6 (9.4)	18.4 (10.2)	2.10	
MO8	7.9 (6.2)	6.7 (5.5)	8.0 (7.0)	1.35	

[a]MO1: Heel, MO2: Lateral midfoot, MO3: Medial midfoot, MO4: Medial forefoot, MO5: Central forefoot, MO6: Lateral forefoot, MO7: Hallux, MO8: Toes.
[b]$**p < 0.01$.
[c]W: Step width.

Table 4. The pressure–time integral at different step width (Unit: Kpas).

Mask[a]	5	10	20	F	Post Hoc
MO1	61.5 (36.0)	63.6 (34.8)	58.9 (19.0)	0.53	
MO2	28.7 (23.7)	35.7 (31.5)	31.1 (16.5)	1.64	
MO3	49.7 (31.1)	42.9 (29.9)	36.6 (13.7)	3.18[b]	W5 > W10 > W20[c]
MO4	68.7 (37.9)	66.2 (29.9)	71.6 (32.0)	0.46	
MO5	54.9 (25.9)	54.2 (24.4)	61.4 (54.6)	0.56	
MO6	49.7 (24.2)	44.2 (20.9)	41.3 (15.9)	2.71[b]	W5 > W10 > W20
MO7	64.8 (42.0)	56.8 (34.8)	60.6 (31.9)	1.28	
MO8	28.2 (23.9)	23.6 (23.2)	22.6 (11.9)	1.77	

[a]MO1: Heel, MO2: Lateral midfoot, MO3: Medial midfoot, MO4: Medial forefoot, MO5: Central forefoot, MO6: Lateral forefoot, MO7: Hallux, MO8: Toes.
[b]*$p < 0.05$.
[c]W: Step width.

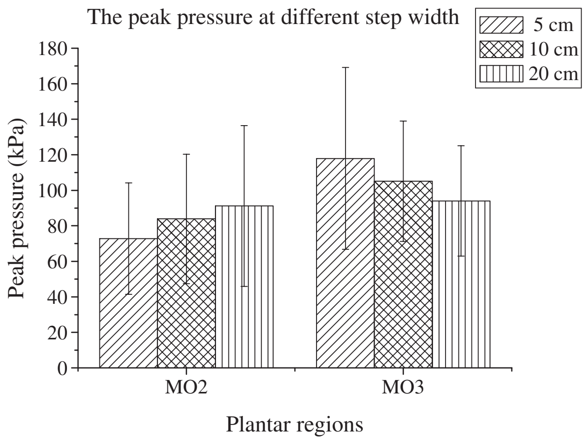

Fig. 2. The peak pressure recorded at different step width. Increasing step width in level walking, the plantar pressure of the medial arch (MO2) significantly increased and that of the lateral arch (MO3) significantly decreased ($p < 0.05$).

medial arch has the maximum pressure of 72.8 Kpa, 83.9 Kpa, and 91.3 Kpa, respectively. With the step width of 5 cm, 10 cm, and 20 cm, the lateral arch has the maximum pressure of 117.9 Kpa, 105.1 Kpa, and 94.0 Kpa, respectively. When the step width was increased during level walking, the plantar pressure of the medial arch

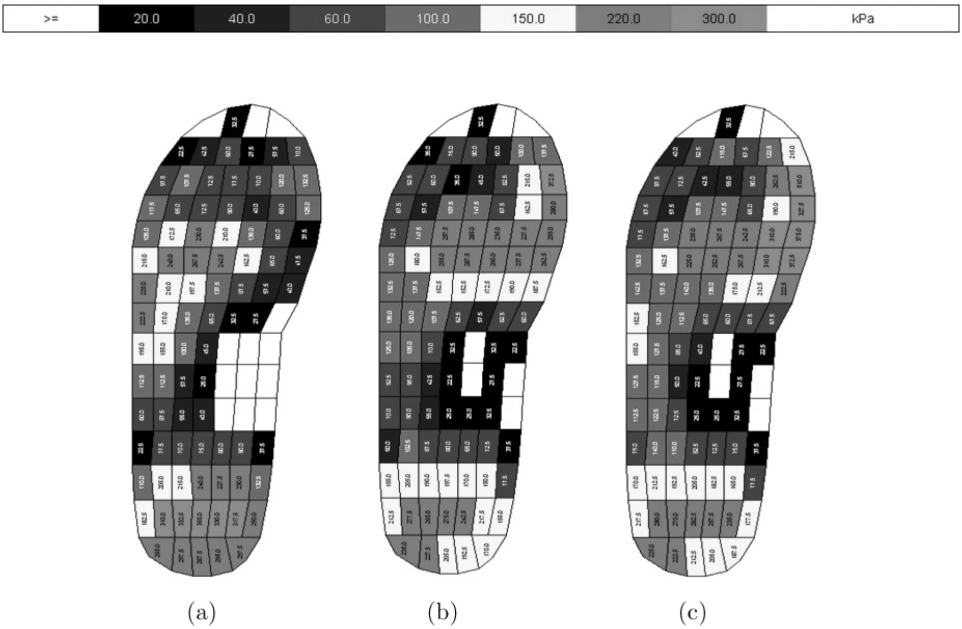

Fig. 3. The peak pressure at different step width for one typical subject: (a) 5 cm, (b) 10 cm, (c) 20 cm.

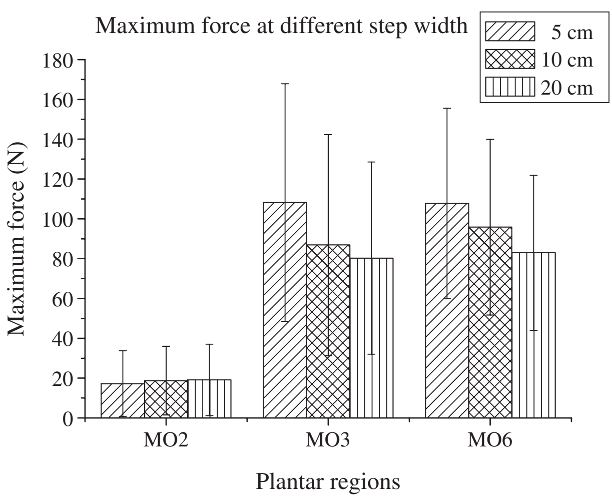

Fig. 4. The maximum force recorded at different step width. Increasing step width in level walking, the maximum force of the medial arch (MO2) increased, that of the lateral arch significantly decreased and that of the lateral forefoot significantly decreased ($p < 0.05$).

significantly increased and that of the lateral arch significantly decreased ($p < 0.05$) (Figs. 2 and 3, Table 1).

The foot is divided into different parts, and this study investigated the maximum force acts on it. The result showed that the plantar pressure in lateral arch significantly decrease with the increasing step width ($p < 0.05$), and the plantar pressure in medial arch increase with the increasing step width. According to the result, the plantar pressure of the medial arch will increase and the lateral arch will significantly decrease when the step width increases. The maximum force distribution of middle arch changes from lateral part to medial part (Fig. 4, Table 2). Considering the pressure–time integral and the force–time integral in the increasing step width, the medial arch has a trend to increase though not significant increase, but the lateral arch (MO3) and metatarsal (MO6) have significant decrease ($p < 0.05$) (Tables 3 and 4).

4. Discussion

The current study showed that walking with an increased step width, the peak plantar pressure on medial arch significantly increased when compared with the peak planar ordinary step width. Meanwhile, maximum force, peak plantar pressure, pressure–time integral, and force–time integral on the lateral arch and the lateral side of metatarsal significantly decreased with increased step width. The reason for these changes in forces and pressure patterns with increased step width during level walking may be induced from the center of gravity (COG) medial deviated relative to the foot placement, which caused the foot relatively pronated. However, kinematics and kinetics changes with different step width walking need to be elucidated in the future.

The tendon of tibialis posterior passes through the ankle joint medially and descends posterior to the medial malleolus. The tendon of tibialis posterior had three parts of insertions at the tuberosity of the navicular, plantar surface of the cuneiforms and cuboid, and into the base of second, third, and fourth metatarsal bases. Consequently, tibialis posterior can act as a strong invertor of the foot. Tome *et al.*[23] measured the foot arch height for patients with posterior tibialis tendon dysfunction and found their arch is lower than normal subjects in phase of stance such as loading response, midstance, terminal stance, and preswing.

By increasing the step width, our results showed the similar foot pressure pattern with pes planus. As the step width increases, the maximum force on medial arch increases and the maximum force on the lateral arch decreases. Increased step width may cause the foot pronation and increase posterior tibialis activation, for stabilizing the arch. As a consequence of change in prolonged gait pattern along with alternations of step width, the posterior tibialis is easily fatigued and become dysfunctional, thus foot deformity and injuries are likely to happen. Also during level walking, plantar pressures are elevated which is considered as an important concern because it has the relations with the risk of tissue injury, foot ulceration,[24] and foot pain.[25,26] Clinicians should not only pay attention to patients' foot–ground reaction[27] but also step width in an effort to help diagnosing and prevent injuries.

In order to decrease the excessive foot pronation, some researchers used low-Dye taping to support longitudinal and transverse arch. Lange *et al.*[8] found mean and peak pressure significantly increased under the lateral midfoot and under the toe, and decrease under the heel and the forefoot after using low-Dye taping in subjects with navicular drop excessive 10 mm. Russo and Chipchase[9] also demonstrated that low-Dye taping significantly altered and decreased peak plantar pressure under the medial midfoot in subjects with normal foot posture. Our findings show the similar foot pressure pattern with low-Dye taping while walking with decreased step width.

Recently, a lot of studies focused on investigating the relations between step width variability, falling, and energy cost in the elderly. Researchers had indicated that extreme step width contribute to the greater energy cost of walking in the elderly[8] and either too little or too much step width variability is associated with falls in frail elderly at normal gait speed.[9] Previous study shows that step width is the important factor to contribute the stability and energy cost during walking. However, few studies investigate the different step width to effect plantar pressure during level walking. Our study shows much step width might increase plantar pressure on medial foot arch. Plantar pressure is associated with foot pain and ulceration. It means plantar pressure alternations of different step width need attention during gait reeducation and gait exercise to avoid falling, instability, and foot injury in the elderly.

In summary, too much step width might cause increase in plantar pressure on the medial foot arch, and the maximum force distribution shifted from the lateral arch to the medial arch. The impulse while foot contact with the ground which should be absorbed by the lateral arch is now absorbed by the medial arch make the shock absorption effect. In long run, the mechanism for shock absorption can be damaged. People with flat foot and lower medial foot arch possibly have a more worse buffering effect in wider step walking. In asymptomatic subjects, greater step-width walking may activate tibialis posterior to maintain the arch stability, it is not only a problem of muscle fatigue but also a problem of foot deformity. Smaller step width can reduce arch depression and maintain the foot arch. As a result, smaller step-width walking is better than greater step width for maintaining the normal foot pressure pattern. It may have the relieving effect for clients with pes planus and it can be a reference for rehabilitation clinicians while treating the above-mentioned subjects. In addition, smaller step-width walking can be promoted to normal population as a new exercise paradigm with an approved scientific basis. However, in this study we used healthy people as the subjects to investigate this pressure pattern change, whether the phenomenon can be found for the clients with pes planus should be investigated in future. Also, smaller step-width walking may increase the risk of falling for those subjects with balance deficiency and the elders, so it is necessary to examine their balance ability before instructing them to perform smaller step-width walking. There are several limitations that must be recognized including experimental device, only female subjects with normal foot, and less number of subjects. This study can further compare the difference between age, sex, and populations with foot deformities to provide the information about different step width as a gait exercise to restore gait function and decrease foot injury during level walking.

5. Conclusion

This study could conclude that with increased step width, the plantar pressure of the medial arch significantly increased and that of the lateral arch significantly decreased. Beside the plantar pressure of the medial arch will increase and the lateral arch will significantly decrease when the step width increases. The maximum force distribution of middle arch changes from lateral part to medial part. It may have the relieving effect for clients with pes planus and it can be a reference for rehabilitation clinicians while treating the above-mentioned subjects.

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