Gait speed and gender effects on center of pressure progression during normal walking

Min-Chi Chiu a,b,*, Hsin-Chieh Wu c, Li-Yu Chang c

a School of Occupational Therapy, Chung Shan Medical University, Taichung 402, Taiwan, ROC
b Occupational Therapy Room, Chung Shan Medical University Hospital, Taichung 402, Taiwan, ROC
c Department of Industrial Engineering and Management, Chaoyang University of Technology, Taichung 402, Taiwan, ROC


A B S T R A C T -The COP progression is the trajectory of the center of foot pressure. Thirty healthy young adults were recruited to participate in this study. All subjects were asked to walk randomly at four different speeds (3 km/h, preferred walking speed, 4 km/h and 5 km/h). A foot pressure measurement system (RS-scan system) was used to collect the center of pressure (COP) coordinates, COP progression angle and the COP velocity. Four sub-phases of the stance phase were calculated. The initial contact (ICP) and forefoot contact phase (FFCP) corresponded to the loading response. The foot flat phase (FFP) coincided with the mid-stance. The forefoot push-off phase (FFPOP) corresponded to the terminal stance and pre-swing phases. The results of this study indicate that the percentage of time (% time) of COP progression on the ICP, FFCP, FFP and FFPOP were approximately 7.0%, 4.8%, 48.8% and 39.4%, respectively. The COP progression angle was 4.1 (SD = 1.6)° with an inward curve and the average COP velocity was 31.6 cm/s (SD = 5.3). The walking speed influenced the % time in the FFP and FFPOP. As the walking speed increased, the % time of COP progression decreased in mid-stance and increased in the terminal and pre-swing stances. Moreover, gender affected the COP progression angle. Men had a significantly larger deviating angle than women during FFCP, FFP and FFPOP. The COP characteristics can offer useful information for clinical rehabilitation in foot functional and structural evaluation.

1. Introduction
The center of pressure (COP) trajectory, or gait line can provide useful information in assessing or detecting foot function and pathology. The center of pressure is the area where an instantaneous force on the plantar surface of the foot acts. This force is a component of the resultant vertical ground reaction force reacting with the foot plantar surface [1]. The COP progression is a path formed by a series of center of pressure coordinates passing from the hind-foot through to the forefoot during the stance phase. Previous studies quantified the COP path and considered it an important sign of the structural and functional foot condition by comparing it with normative reference data. The COP displacement
is about 83% of the foot contact length and 18% of the forefoot contact width for middle-aged adults [2]. In children the COP progresses under the heel, midfoot and forefoot regions at about 23.8, 28.7 and 47.5 time % of a complete stance phase, respectively [3,4]. Moreover, the COP velocity is one of the most valuable indicators in describing gait performance. The COP velocity is approximately 22–27 cm/s and 38 cm/s for middle-aged adults and young adults, respectively [2–4]. The COP velocity displays a triple-peak pattern with the first peak occurring in the rear foot at between 0% and 20% percent of the stance time. The second and third peaks occur at approximately 35% and 92% of the stance phase, respectively [5]. De Cock et al. [1] interpreted the COP trajectory during barefoot running for young adults and indicated that the COP displacement and velocity provided information on arch structure. Gender and dominance (right or left foot) did not have any significant influence on the COP course [6]. Analysis of variation in normal walking has shown that speed and gender are critical factors determining gait kinematics and kinetics. Faster walking speed leads to increased range of motion (ROM) in the hip and knee joints, higher vertical ground reaction force (VGRF) at heel strike and lower VGRF during foot flat contact [7,8]. Increased walking speed also results in significantly greater ROM at the tibio-talar joint, the medial arch and the hallux in the sagittal plane and more abduction motion in the hallux in the transverse plane [9]. Women display more plantar flexion at toeoff and during initial swing as well as higher ankle plantar flexion and abduction moments than men [10,11]. Men appear to display a more external foot progression angle than women throughout stance, while there is no difference in swing [10]. The influence of walking speed and gender on COP progression remains unclear. This study aims to define the walking speed and gender effects on the COP pathway. The COP progression characteristics for young adults will also be presented in this study. The walking speed and gender effects on the COP trajectory will be assessed by measuring the COP spatio-temporal progression parameters, progression angle and velocity.

2. Methods

2.1. Subjects
Thirty healthy young adults (15 women and 15 men) participated in this study. The average age of these subjects was 23.6 (SD = 2.7) years, the average height was 167.6 (SD = 7.7) cm, and average weight was 59.8 (SD = 10.2) kg. All subjects had no history of musculoskeletal disorder or lower extremity injury within the previous year and had a normal arch based on assessment of the static pressure footprint. The arch was considered normal when the arch index (AI) was 0.21 < AI < 0.26 as defined by Cavanagh and Rodgers [12]. Table 1 displays the subjects’ information including foot anthropometric data, preferred walking speed (PWS) and cadence.

2.2. Experimental design
A nested-factorial experimental design was employed. Two independent variables were walking speed (3, PWS, 4, and 5 km/h) and gender (women and men). Subjects were asked to walk along the walkway at four different speeds, randomly. The measurements included: (1) the x-, y-coordinates of the center of pressure (COP), (2) the velocity of COP and, (3) the progression angle of COP.
2.3. Response measures and instruments

2.3.1. Foot pressure measurement system

A dynamic pressure measurement system (footscan system, RSscan International, Belgium) was used to record the COP coordinates, velocity and progression angle. The hardware included a 0.5 m plate with 4 sensors/cm² and a 3D-Box interface which was synchronized with the motion capture system. All data were recorded at a measurement frequency of 500 Hz and processed using Scientific footscan software (RSscan International, Belgium). For the x-, y-coordinates of the center of pressure (COP) (Fig. 1a); the longitudinal foot axis (y-axis) was defined as the line (FFCP) which is the period immediately following ICP, until all metatarsal head areas make contact with the pressure plate. The third sub-phase is the foot flat phase (FFP) which follows FFCP and ends when the heel is off the ground. The fourth sub-phase is the forefoot push-off phase (FFPOP) which starts when the heel is off the floor and ends when the foot is off the from the rear foot (middle heel) to the forefoot, over the second metatarsal. The x-axis was perpendicular to the y-axis. The original absolute x- and y-coordinates were calculated to the relative x- and y-coordinates and plotted as the COP path. The software of Matlab version 7.0 (Mathworks Inc.) (Polynomial interpolation) was applied to calculate the relative x- and y-coordinates. According to the Scientific footscan software (RSscan International, Belgium), stance phase can be divided into four phases (as Fig. 1a). The first one is the initial contact phase (ICP) which is defined as the period from first foot contact until first metatarsal contact. The secondary sub-phase is the forefoot contact phase ground.

2.3.2. Motion capture system

In order to monitor the walking speed, a six-camera (Charge Coupled Device/CCD) motion capture system (VICON 460 Motion System, Oxford Metrics Ltd., UK) was applied to record the pelvic displacement while
stepping on the walkway. The sampling rate was 120 Hz with low-pass filtering at 6 Hz. The Helen Hayes marker protocol was used only for the pelvis and three reflecting markers were placed at the right anterior superior iliac spine, left anterior superior iliac spine and sacrum, respectively. Thus, the pelvic segment coordinate system could be defined and the pelvis displacement could be calculated. The software of Matlab version 7.0 (Mathworks Inc.) was applied to calculate the pelvic motion and walking speed.

2.4. Experimental procedure
All subjects were volunteers and provided informed consent. Some basic information (body weight and height) and the relevant foot anthropometric data were initially collected. Subjects were asked to walk barefoot on a treadmill at a specified speed (PWS, 3 km/h, 4 km/h, and 5 km/h). For the PWS condition, participants began walking on the treadmill at a relatively slow speed. The subjects then increased speed at 0.1 km/h increments until they reported that they were walking at their PWS. Then 1.5 km/h was added to the current speed, followed by a decrease of 0.1 km/h to re-establish PWS [13]. During this process the subjects were blind to the digital speed display. This procedure was repeated three times. The walking speeds were then averaged to determine the PWS. During treadmill walking a metronome was used to define the individual’s walking tempo. After treadmill walking the subject followed the tempo paced by the metronome to maintain the same walking speed while continuing to walk along a rectangular walkway (8 m × 3 m, and 0.6 m width path). During each trial the subject walked continuously until thirty steps were recorded fully. Data recorded during walking on the 8-m straight walkway were taken from the subject’s right foot (dominant side), and measurements included the COP coordinates, progression angle and COP velocity.

2.5. Data analysis
For data consistency, the trial to trial reliability of the x-, y-coordinates of COP was tested using intraclass correlation coefficients (ICC2,1) and 95% confidence intervals. According to Shrout and Fleiss, the ICC values were interpreted (excellent reliability > 0.75 > good reliability > 0.40 > fair reliability) [14]. Analysis of variance (ANOVA) was conducted to assess the walking speed and gender effects on the COP progression characteristics. Post hoc testing was conducted using Duncan’s multiple range tests. Statistical analyses were performed using the SPSS version 14.0 statistical analysis software.

3. Results
3.1. Reliability of measurements
The COP displacement was recorded using the x- and y-coordinates. The COP displacement in the medial-lateral and anterior-posterior directions were regarded with respect to the x and y-axes, separately (as Fig. 1a). For data consistency, betweentrial reliability, intra-class correlation coefficient (ICC) measurement was used to calculate the absolute COP x- and y-coordinates. As shown in Table 2 the trial-to-trial reliability of the COP variables for the x-coordinate ICCx was between 0.55 and 0.90 and the ICCy for the y-coordinate was between 0.93 and 0.98 at different walking speeds and gender.

The results indicated good to excellent reliability for the COP variables during barefoot walking.

<table>
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<tr>
<th>Table 2</th>
<th>Intra-class correlation coefficients (ICC) for the x- and y-COP coordinates.</th>
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<tr>
<td>Variables</td>
<td>ICCx</td>
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<tr>
<td>Men</td>
<td>3 (km/h)</td>
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<tr>
<td></td>
<td>PWS</td>
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<td></td>
<td>4 (km/h)</td>
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<td></td>
<td>5 (km/h)</td>
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<tr>
<td>Women</td>
<td>3 (km/h)</td>
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<td></td>
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<td>4 (km/h)</td>
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<td>5 (km/h)</td>
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* Preferred walking speed is 3.7 km/h. 
* Significant at p < 0.05.
3.2. The spatio-temporal parameters of COP progression

As shown in Table 1, there were significant differences in body height, weight and relevant foot anthropometric data between women and men (p < .05). However, there were no significant differences in PWS and cadence between women and men (p > .05). For all subjects, the PWS was 3.7 km/h (SD = 0.4) with an average cadence of 101.2 steps/min (SD = 8.7). The distribution of x- and y-coordinates of COP under plantar region varies with subject’s foot size. Foot length and width for all subjects were averaged as the “standard foot” with foot length (24.5 _ 1.4 cm) and foot width (8.9 _ 0.6 cm). The original absolute x-and y-coordinates were calculated to the relative x-and y-coordinates and the mean curves of all trials for an individual were computed. The displacement of the COP progression for all subjects was plotted on the standard foot. As shown in Fig. 1b, the total COP progression trajectory was almost 95% of the foot length and 31% of the forefoot width. Moreover, the COP progression time % in the ICP, FFCP, FFP and FFPOP sub-phases were approximately 7.0%, 4.8%, 48.8% and 39.4%, respectively (Fig. 1b). Table 3 displays the ANOVA and Duncan’s multiple range test results on the walking speed and gender effects. Walking speed significantly influenced the COP progression time % during FFP and FFPOP (p < .05). The post hoc Duncan’s multiple range test results showed that when walking at 5 km/h, significantly less time % was spent on FFP than walking at slower speed. The same test showed relatively more time % on FFPOP while walking at 5 km/h (Fig. 2). This result suggests that with increasing walking speed, the COP progression time % in FFP diminishes and increases in FFPOP.

3.3. The COP progression angle

The COP progression angle was calculated from the relative COP displacement, which is the angle between the COP direction progression and the long axis of the foot. For the x-axis a lateral direction is signed as positive (+) degrees and the medial side direction is signed as negative (−) degrees. For healthy adults, the averaged COP progression angle was −4.1 (SD = 1.6) degrees with an inward curve. Although walking speed did not have a significant influence, gender did have a significant influence on the progression angle (Table 3). In general, men revealed greater deviations in
Fig. 2. The time percentages (time %) of COP progression during (a) 3 km/h; (b) PWS (3.7 km/h); (c) 4 km/h and (d) 5 km/h walking speed.

<table>
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<tr>
<th>Table 3</th>
<th>The ANOVA and Duncan’s multiple range test results for COP time t, progression angle and velocity.</th>
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<tr>
<td>Measurements</td>
<td>Variations</td>
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<td>Time % of COP progression</td>
<td>ICP</td>
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<td>Progression angle of COP</td>
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<td>COP</td>
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Note: Preferred walking speed is 3.7 km/h.

3.4. The velocity of COP progression

The averaged COP velocity for all subjects was 31.6 (SD = 5.3) cm/s. Table 3 indicates that the COP velocity was significantly affected by walking speed (p < .05). Walking at 5 km/h exhibited the highest COP velocity compared to 4 km/h, PWS, and 3 km/h. In the four sub-phases, walking at a higher speed caused faster COP velocity simultaneously in ICP, FFCP, FFP and FFPOP (p < .05). There were no interactions between the walking speed and gender variables in the COP progression time %, progression angle and velocity (p > .05).

4. Discussion

4.1. The characteristics of COP progression

Many studies have investigated the relationship between plantar pressure and foot structure or pathology. There are challenges in obtaining qualified, standardized measurements of plantar pressure. In this study the COP displacement showed good inter-trial reliability during the barefoot walking tests, consistent with that in previous studies [1,2]. The COP course could be more reliable and practical for clinical assessment of foot structure. Women and men have different anthropometric characteristics. However, there were no differences found in PWS and cadence in this study. This would suggest that gender differences in lower extremity dimensions did not relate to PWS [7].

Foot size was normalized into a standard foot and the original COP displacements were transferred into the relative coordinates to graphically represent the COP progression. The full COP course under the plantar region corresponded to 95% of the foot length and 31% of the foot width. The average COP velocity was 31.6 (SD = 5.3) cm/s. Compared with previous studies, the diversity in COP position and velocity were probably due to dissimilar measurement systems, age and walking speed [2,5]. For the four sub-phases of COP trajectory, the initial contact (ICF) and forefoot contact phases (FFCF) correspond to the initial contact and landing responses of the stance phase. During initial contact, the slight medial shift in COP may display the...
fast initial foot pronation (heel eversion) for loading shock absorption [6,16]. Following the loading response, the lateral shift in COP reveals the longitudinal arch of the foot delivering the load towards the lateral border [1,6]. A faster COP velocity indicates a rapid forward weight shift in COP during this phase. Afterward, the foot flat phase (FFP) or midstance comprises the period during which the body weight continuously passes over the foot and the foot changes from a flexible to a rigid structure. The COP advances forward steady with the ankle joint dorsiflexion and heel rises. Finally, the terminal and pre-swing phase occurs in accordance with the forefoot push-off phase (FFPOP). When the COP passes through the heel off stage, an observable medial shift appears for propulsion. A push off over the medial metatarsals and the great toe is revealed. The medial-lateral preceding COP deviation during these four sub-phases could be an important determinant for foot structure and function. For young adults, the temporal-spatial COP features through the ICP, FFCP, FFP and FFPOP occupied approximately 7.0%, 4.8%, 48.8% and 39.4% of stance time, respectively. During jogging, the duration for these four sub-phases was found to be 8.2, 11.3, 25.3, and 55.1 stance time % [6]. The different time % indicate different foot roll-over temporal characteristics between walking and running. The slope of the COP coordinates for middle-aged adults during stance phase was approximately 6° inward [2]. For young adults the average COP progression angle was 4.1 (SD = 1.6)° with an inward curve in four different walking speeds (3 km/h, 3.7 km/h, 4 km/h and 5 km/h). 4.2. Walking speed and COP progression Because walking speed has an influence on kinematic and kinetic walking variables [7,9], walking speed alters the temporal COP path features as well. It is interesting that as walking speed increases the COP progression time % decreases in FFP and increases in FFPOP. Faster walking speed tends to produce a relatively faster body weight shift from the rear foot to the forefoot. This suggests an earlier heel off with increased walking speed [6]. Moreover, the COP progression angle may be influenced by walking speed. However, the walking speed effect on the progression angle was not significant in this study. This might be due to a slight variability in normal walking speeds (between 3 and 5 km/h in this study) not being clearly confirmed. It was reasonable that faster walking speed caused higher COP velocity. It also could be expected that higher walking speeds produce higher COP velocity simultaneously in the four sub-phases. Walking at 5 km/h speed led to higher average COP velocity and higher COP velocity in ICP, FFCP, FFP and FFPOP.

4.3. Gender and COP progression
This study found no significant differences in spatio-temporal COP features and velocity between women and men. This is consistent with the results of De Cock et al. [6] suggesting no significant gender influence on the COP course. On the other hand, gender differences in the knee and ankle kinematics in the sagittal plane were found in some studies [10]. The results of this study indicate that gender significantly affected the COP progression angle. Men had a greater external progression curve during the forefoot contact phase (FFCP). A greater lateral shift during the FFCP would suggest that men had less rearfoot (calcaneus) eversion than women during the forefoot contact phases [15]. Men displayed a more internal progression angle during the forefoot flat and forefoot push off phases. This would imply that women displayed more forefoot variation than men during propulsion. The fact that differences in COP progression angle between genders were apparent suggests gender variance in the ankle and foot kinematics during the stance phase. These results imply that women and men use different strategies to control their ankles and feet when walking.
normally. In summary, this study discussed the COP progression characteristics in adults. Walking speed affects the time % for COP progression during the foot flat and forefoot push-off phases. With increased walking speed, the COP velocity increases significantly. Moreover, gender significantly influenced the COP progression angle. COP progression analysis could provide more useful information to foot functional and structural evaluation.

Conflicts of interest statement
There is no conflict of interests in terms of financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work, all within 3 years of beginning the work submitted.

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