

Published in final edited form as:

Gait Posture. 2014 May ; 40(1): 252–254. doi:10.1016/j.gaitpost.2013.12.023.

Center of Pressure Trajectory during Gait: A Comparison of Four Foot Positions

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Abstract

Knowledge of the center of pressure (COP) trajectory during stance can elucidate possible foot pathology, provide comparative effectiveness of foot orthotics, and allow for appropriate calculation of balance control and joint kinetics during gait. Therefore, the goal of this study was to investigate the COP movement when walking at self-selected speeds with plantigrade, equinus, inverted, and everted foot positions. A total of 13 healthy subjects were asked to walk barefoot across an 8 meter walkway with embedded force plates. The COP was computed for each stance limb using the ground reaction forces and moments collected from three force plates. Results demonstrated that the COP excursion was 83% of the foot length and 27% of the foot width in the anterior-posterior and medial lateral directions for plantigrade walking, respectively. Regression equations explained 94% and 44% of the anterior-posterior and medial-lateral COP variability during plantigrade walking. While the range of motion and COP velocity was similar for inverted and everted walking, the COP remained on the lateral and medial aspects of the foot for these two walking conditions, respectively. A reduced anterior-posterior COP range of motion and velocity was demonstrated during equinus walking. Ankle joint motion in the frontal and sagittal planes supported this COP movement, with increased inversion and plantar flexion demonstrated during inverted and equinus conditions, respectively. Results from this study demonstrated the COP kinematics during simulated pathological gait conditions, with the COP trajectory providing an additional tool for the evaluation of patients with pathology.

Introduction

The center of pressure (COP) movement has been identified as a measure of neuromuscular control during posture and gait. Defined as the centroid of all the external forces acting on the plantar surface of the foot, the COP movement has further been used to identify balance control, foot function, and treatment efficacy.^{1,2} The COP velocity has additionally been

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Conflict of Interest The authors have no conflicts of interest to declare.

shown to be a reliable measure of gait efficiency, with its clinical usefulness hypothesized for patients with hallux limitus or rigidus, metatarsalgia, hallux abducto valgus, or lower-limb amputation.³ Among patients with hallux valgus and metatarsalgia an increased COP velocity was previously demonstrated during gait, when compared to normal feet.⁴

While studies have demonstrated the efficacy of using both plantar pressure devices and force plates to record COP,^{1,5,6} with normative COP trajectories and velocities determined during walking³ and running,⁷ no investigations have demonstrated the differences in COP kinematics during various gait conditions. Therefore, the purpose of this study was to investigate the COP movement when walking under normal and modified gait conditions. We hypothesized that the COP range of motion (ROM) would be greatest during plantigrade gait, with reduced COP movement and increased COP velocity demonstrated during simulated pathological gait.

Methods

A total of 13 healthy young adults (8 females, age 25.1 ± 2.9 years), were asked to walk barefoot across an 8 meter walkway using four different foot conditions: 1) plantigrade; 2) equinus; 3) inverted; and 4) everted. During equinus, inverted, and everted walking, subjects ambulated on their toes, lateral borders of their feet, and medial borders of their feet, respectively, in order to simulate walking with pathology. All participants provided written informed consent prior to involvement in the study. The study protocol was approved by the Mayo Clinic Institutional Review Board.

Three-dimensional trajectories of 12 reflective markers bilaterally placed on the feet (calcaneus, midpoint of the 2nd and 3rd metatarsal-phalangeal joint, 1st proximal metatarsal, 1st distal metatarsal, 5th proximal metatarsal and 5th distal metatarsal) and eight reflective markers bilaterally placed on the shank (lateral malleolus, medial malleolus, lateral epicondyle and midpoint of the lateral epicondyle and lateral malleolus) were collected using a 10-camera motion analysis system (Motion Analysis Inc., Santa Rosa, CA). Ground reaction forces and moments were collected from three force plates (AMTI Inc., Watertown, MA and Kistler Inc., Amherst, NY). Kinematic and kinetic data was collected at 120Hz and 720Hz, respectively. Foot anthropometrics collected included navicular height, foot length and foot width.

The COP was computed for each limb throughout stance from the measured ground reaction forces and moments. The COP was converted into the foot coordinate system, with data normalized in the anterior-posterior and medial-lateral direction based on the foot length and foot width, respectively. The COP velocity was calculated using the Savitzky-Golay least squares method of differentiation, with the polynomial order set to 5 and the window length set to 11.⁸ Ankle joint kinematics were calculated using a y-x-z Cardan sequence, where x represents the anterior-posterior axis, y the medial-lateral axis, z the superior-inferior axis. The arch index was calculated as the ratio of navicular height and the distance from the calcaneus to the first metatarsal-phalangeal joint during single-leg quiet standing.⁹ All computations were performed using custom MATLAB programs (MathWorks Inc., Natick, MA).

Differences in the COP ROM and velocity (VEL) across walking conditions were evaluated using a one-way ANOVA. A comparison of loaded foot arch index and the COP ROM was performed using a Spearman's rank correlation in order to investigate COP changes due to foot anthropometrics. A forward stepwise linear regression was performed to estimate the medial-lateral and anterior-posterior COP during all walking conditions (IBM SPSS Inc., Chicago, IL). An increasing order polynomial of percent stance was inserted or removed from the regression equation if the F test was less than 0.05 or greater than 0.10, respectively.

Results

A total of 26 feet were evaluated across all four walking conditions, with the COP traversing the forefoot, lateral boundary, or medial boundary of the foot during equinus, inverted, and everted walking, respectively. On average, the COP remained along the midline, the lateral portion, and the medial portion of the foot, during midstance for plantigrade, inverted and everted walking, respectively (Fig. 1). Towards end of stance, the COP progressed to the 1st metatarsal-phalangeal joint for all conditions. The COP demonstrated a relatively large medially directed velocity at heel strike and toe off, with a constant anteriorly directed velocity throughout stance for plantigrade, inverted, and everted walking.

Participants demonstrated a significant condition effect for both the anterior-posterior and medial lateral COP ROM (Fig 2; $P < 0.001$). The equinus walking condition demonstrated differences from all other conditions ($P < .001$), with the COP traversing across approximately 26.1% ($\pm 6.8\%$) of the foot length and 41.2% ($\pm 12.8\%$) of the foot width. The inverted walking condition also demonstrated a 10% greater COP ROM in the medial lateral direction than everted walking ($P = 0.036$).

Investigation of ankle joint angles across the four gait conditions revealed kinematic differences in all three planes. In the sagittal plane, equinus gait demonstrated on average 15 degrees of increased plantar flexion during stance (Figure 3; $P < 0.001$). In the frontal plane, inverted and everted gait demonstrated approximately 9.6 and 0.7 degree of inversion, respectively, compared to the 4.5 degrees of inversion during plantigrade and equinus gait ($P < 0.001$).

The variability explained for the COP position in the anterior-posterior direction was greater than 80% for plantigrade, inverted, and everted walking (Table 1). Reduced R^2 values were revealed for the anterior-posterior COP movement during equinus walking and all four medial-lateral COP movements.

Over the 26 feet tested, the arch index ranged from 18.6 to 27.5 (average (SD) of 22.6 (2.6)). The arch index was not correlated with the COP ROM for any measure except for the anterior posterior COP ROM during inverted walking ($r = 0.564$; $p = 0.007$).

Discussion

The goal of this study was to describe the COP movement across the plantar foot surface during plantigrade, equinus, inverted, and everted walking. While previous research has

modeled the COP progression linearly,¹⁰ results of a regression analysis reveal that the COP trajectory is a more complicated movement, involving at least polynomial expressions of the stance time. While there was a reduced amount of variance explained for the COP trajectory in the medial-lateral direction for all foot conditions, among everted, inverted, and plantigrade walking, up to a third order polynomial expression of stance explained greater than 80% of the COP movement in the anterior-posterior direction. In contrast to our hypothesis, the greatest medial-lateral COP ROM was demonstrated during the equinus condition, with similar COP ROM and COP velocity demonstrated during plantigrade, inverted, and everted gait.

The average trajectory of the COP during plantigrade walking is similar to results previously demonstrated using both force plates and foot pressure systems.^{1,4} While a similar pattern of movement is seen during inverted walking, the COP is placed approximately 5% of the foot width further laterally during midstance, when compared to plantigrade walking. Alternatively, during everted walking, the COP was always on the medial portion of the foot. Clinically, reducing eversion of the foot during gait can result in reductions in frontal and transverse plane knee joint motion.¹¹ While orthotic decisions are often based on measurements taken during static posture,¹¹ understanding of the dynamic COP trajectory can provide additional information related to lower extremity moments and balance control during gait.^{12,13} The use of a biomechanical device to manipulate the COP in the medial and lateral direction has previously demonstrated significant correlations between the COP shift and the location of the device.¹⁴ The placement of such devices allowed for direct control of the COP, which could have implications for implant design and practice.¹⁴

The COP velocity has previously been shown to range from 16cm/s to 27cm/s and 19cm/s to 24 cm/s for men and women, respectively, from loading response to preswing when wearing flat heeled shoes.⁶ While similar results were seen in the current study for participants during midstance, large COP velocities were demonstrated at heel strike and terminal stance across all walking conditions. Differences might be indicative of the effect from shoe insoles on the COP.

Results of the COP ROM are similar to those reported previously, in which the COP displacement corresponded to 83% of foot contact length and 18% of foot contact width.⁶ The COP ROM further demonstrated up to 10% differences in the medial lateral direction across gait conditions. Interestingly, the arch index did not affect the COP ROM, with the COP trajectories demonstrating small standard deviations across all gait conditions. These results are in contrast to subjects with a higher arch demonstrating a reduced medial-lateral COP ROM during running.⁷ Though a limitation of this study is the lack of individuals with foot instability, results of this study provide representative trajectories for the COP among healthy individuals during simulated pathological gait. Future work can hopefully utilize these normative values in the potential diagnosis and evaluation of patients with pathology.

Acknowledgments

Funding was provided by NIH T32 HD07447.

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Highlights

- 1) We compare the dynamic stability margin using both Tekscan and Marker systems.
- 2) Interaction of the center of mass and base of support defined stability.
- 3) Subjects walked under plantigrade, equinus, inverted and everted conditions.
- 4) The two base of support calculations demonstrated RMS differences from 0.9 to 3.5cm.
- 5) Ensure similar definitions of the base of support are used when comparing stability.

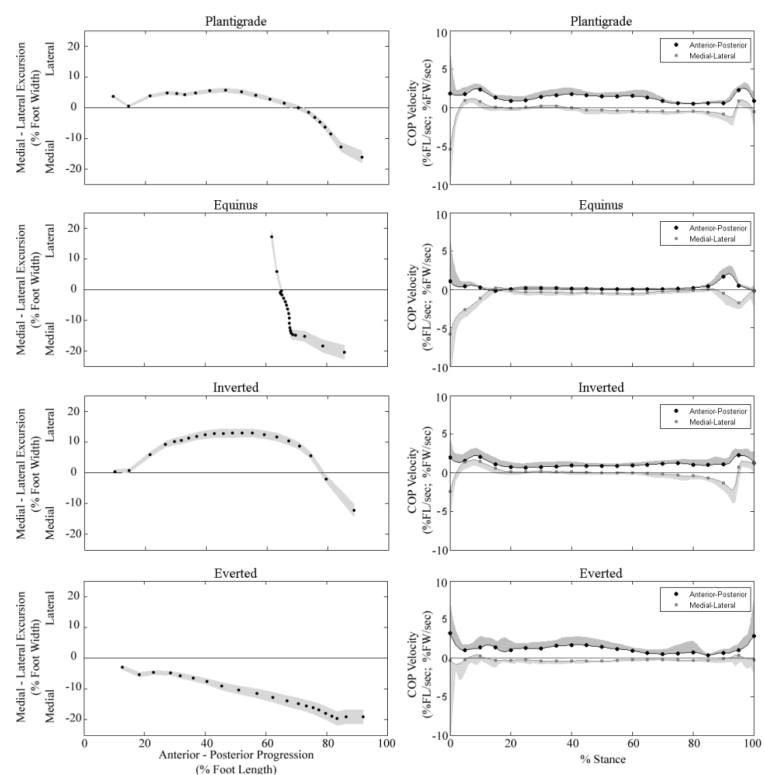


Figure 1. Average (± one SD) excursion of the COP displacement and velocity over the four walking conditions. Each point of the COP displacement and velocity represents 5% of stance.

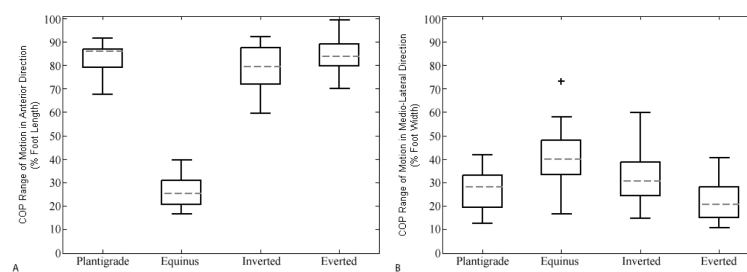


Figure 2.

COP range of motion across four conditions. The central dashed line represents the median, the box edges are the 25th and 75th percentiles, and the whiskers extend to ± 2.7 SD. Outliers are labeled as +.

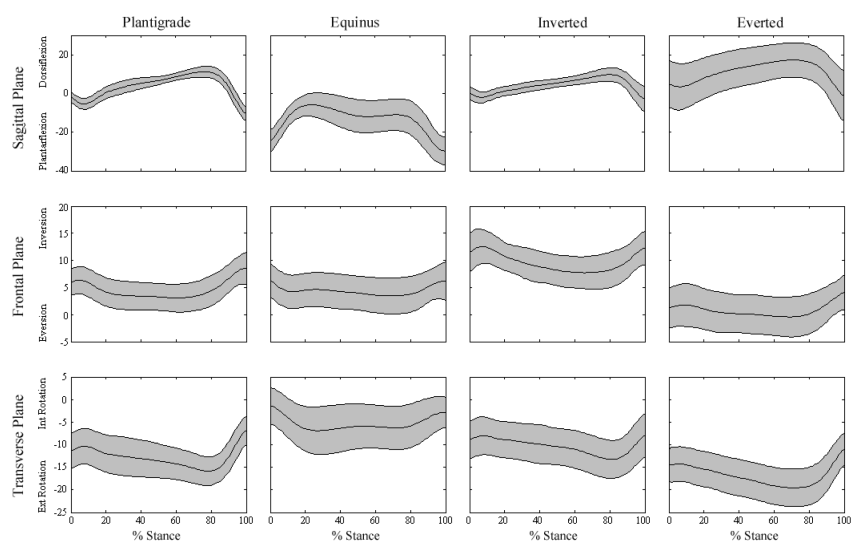


Figure 3.
Average (\pm one SD) ankle kinematics during stance over the four walking conditions.

Table 1

Regression results for COP movement in both the anterior-posterior and medial-lateral directions under four foot positions. T indicates the percent of stance. All coefficients included are significant at the level of $p < 0.05$.

Position	COP Direction	Equation	R ²
Plantigrade	Anterior - Posterior	$0.093 + 1.093*T - 0.300*T^2$	0.938
	Medial - Lateral	$0.294*T - 0.455*T^2$	0.443
Equinus	Anterior - Posterior	$0.611 + 0.436*T - 1.092*T^2 - 0.863*T^3$	0.273
	Medial - Lateral	$0.091 - 0.620*T + 0.731*T^2 - 0.401*T^3$	0.387
Inverted	Anterior - Posterior	$0.113 + 1.033*T - 1.060*T^2 + 0.783*T^3$	0.875
	Medial - Lateral	$0.009 + 0.382*T - 0.448*T^3$	0.331
Everted	Anterior - Posterior	$0.122 + 1.039*T - 0.284*T^3$	0.797
	Medial - Lateral	$-0.031 - 0.179*T$	0.250