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Original Article

Effect of foot progression angle alteration on medial–lateral center of pressure position during single-leg standing

Toshihiro Haba, RPT, MS[1)*], Hiroyasu Iwatsuki, RPT, PhD[1)]

[1)] *Department of Physical Therapy, Aomori University of Health and Welfare: 58-1 Hamadate Mase, Aomori-shi, Aomori 030-8505, Japan*

Abstract. [Purpose] This study aimed to investigate the effect of altering the foot progression angle (FPA) on the center of pressure (COP) position during single-leg standing. [Participants and Methods] Fifteen healthy adult males participated. The participants performed single-leg standing on the left leg in three different FPA conditions, namely toe-in, neutral, and toe-out, in which the FPA was set to 0°, 10°, and 20°, respectively. The COP positions and pelvis angles were measured using a 3D motion analysis system, and each measurement value among the three conditions was compared. [Results] The medial–lateral COP position differed among conditions in the coordinate system based on the laboratory condition but did not differ in the coordinate system based on the longitudinal axis of the foot segment. Moreover, no changes were observed in pelvis angles that would affect COP position. [Conclusion] Altering the FPA does not change the medial–lateral position of the COP during single-leg standing. Here we show that COP displacement based on the laboratory coordinate system is involved in the mechanism-linking alteration of FPA and changes in knee adduction moment.

Key words: Foot progression angle, Center of pressure, Single-leg standing

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INTRODUCTION

Increased external knee adduction moment (KAM) indicates mechanical loading on the medial compartment of the knee joint and is associated with the progression and severity of knee osteoarthritis[1)]. KAM is expressed as the vector product of the ground reaction force vector in the frontal plane and the perpendicular distance (lever arm) from the ground reaction force vector to the knee joint center in the frontal plane[2)]. Several gait modifications have been proposed as conservative treatments for patients with knee osteoarthritis to reduce KAM, and the alteration of foot progression angle (FPA) has been recognized to be effective for gait modification[3–5)].

In general, FPA is defined as the angle between the long axis of the foot, which is the line between the heel and the second metatarsal head, and the walking direction[6)]. In addition, increased FPA is considered toe-out and it decreases KAM in the late stance phase during gait[5)]. This mechanism is inferred to result from the reduction of the lever arm following the displacement of the center of pressure (COP)[5)]. Similarly, toe-in decreases KAM by reducing the lever arm in the early stance phase during gait[4)].

However, recent studies reported that the biomechanical effects of FPA were inconsistent among individuals[7, 8)]. Moreover, the mechanisms linking the alteration of FPA to changes in KAM are not entirely understood, and experimental data to support this theory is lacking[4)]. The lever arm is determined by the COP position, knee joint center position, and direction of the ground reaction force vector. Therefore, despite the importance of understanding the effects of FPA on COP, to the best of our knowledge, no studies have investigated COP position within the plantar.

*Corresponding author. Toshihiro Haba (E-mail: t_haba@auhw.ac.jp)

This fact complicates the interpretation of studies linking alterations in FPA to changes in KAM. Moreover, if the COP position within the plantar changes, the effect on the ankle joint moments must be considered. Therefore, the objective of this study was to investigate the effect of altering the FPA on COP position. We hypothesized that the increase in FPA displaces the COP position laterally on the frontal plane but does not change the COP position within the plantar. The results of this study are useful for understanding the effects of FPA on COP. Moreover, if it does not change the COP position within the plantar, it proves that altering the FPA is effective for gait modification.

PARTICIPANTS AND METHODS

Fifteen healthy adult males participated in this study (age: 20.9 ± 1.0 years; height: 171.4 ± 6.1 cm; weight: 63.7 ± 5.8 kg). Participants were those who responded to the call for posters. The participants were randomly recruited using invitations on posters and confirmed to have no history of spinal or lower limb orthopedic diseases or disease that affected equilibrium. This study was conducted with the approval of the Aomori University of Health and Welfare Ethics Committee (No.21015). In addition, informed consent was obtained from all participants.

Participants performed single-leg standing (SLS) on the left leg in three different FPA conditions. A previous systematic review[3] found that the FPA in natural gait is 10°, and a 10° difference in FPA provides sufficient biomechanical change[9–11]. Therefore, the three FPA conditions were configured with toe-in, neutral, and toe-out, and the FPA was set to 0°, 10°, and 20°, respectively. Moreover, the supporting leg in the SLS was defined as the pivot leg when kicking the ball, and all participants used the left leg as the pivot leg. All participants completed the SLS in the neutral condition, followed by SLS in the toe-in and toe-out conditions in random order. As our objective did not involve investigating the effect of altering FPA on KAM reduction, a motor task wherein the plantar was completely in contact with the floor was selected. In addition, because the trunk movements that affect COP position had to be controlled, SLS was selected as the motor task.

Sixteen retroreflective markers with a 14-mm diameter were attached to the participants according to the Plug-in-Gait lower body model. In addition, a marker was added to the dorsum of the foot at 50% of foot length to evaluate the arch height[12]. FPA, pelvis angles, external ankle eversion moment, arch height, and COP position were measured using a 3D motion analysis system with eight infrared cameras (VICON MX, Vicon, Oxford, UK) and two force plates (OR 6–6-2000, AMTI, Watertown, MA, USA) synchronized at a 100-Hz sampling frequency. The measured data were processed using Vicon Nexus 2.3; additionally, after removing noise using a low-pass filter (Butterworth filter; cutoff frequency: 6 Hz), each parameter was calculated according to the definition (Table 1).

The SLS was begun on the author's verbal command from a standing position with a distance of 20 cm between the first metatarsal heads of both feet. Participants were asked to fold their arms in front of the chest, lift the contralateral leg up to a height of 5 cm, and maintain this height for 10 s. In addition, participants were instructed to gaze at a certain viewpoint of 3 m (height: 150 cm) in front of the eye to maintain the knee joint in the extended position and maintain the trunk and pelvis in the median position as much as possible. To minimize the effect of pelvic obliquity during SLS, a digital inclinometer (Eformation Technology Limited, Hong Kong) was attached to the pelvis (second sacral vertebra), and the participants were required to maintain the pelvis horizontal within a range of ± 1° using the alarm function. SLS was performed after sufficient practice; however, in cases where obvious agitation during the measurement rendered difficulty in maintaining the trunk or pelvis horizontal, the measurement was undertaken again.

Table 1. Definition of each measurement parameter

Measurement parameters	Explanation of definitions
Foot length	Distance between the most posterior portion of the calcaneus and the end of the longest toe by anthropometry.
Foot width	Distance between the first metatarsal and fifth metatarsal head by anthropometry.
Foot progression angle (FPA)	Angle between the line connecting the heel and the second metatarsal head measured by 3D motion analysis system and the sagittal axis in the laboratory.
Pelvis angles	Absolute angle based on the Global coordinate system calculated by the x-y-z Cardan ordered sequence.
External ankle eversion moment	External ankle eversion moment calculated by inverse dynamics and normalized by body weight.
Arch height	Distance between the marker which was attached to the dorsum of the foot at 50% of foot length and the floor measured by 3D motion analysis system.
Center of pressure (COP)-X	Position of the COP in the medial-lateral direction from the ankle joint center, with the lateral direction indicating a positive value.
COP-Y	Position of the COP in the anterior-posterior direction from the ankle joint center, with the anterior direction indicating a positive value.

In data analysis, stable 3-s averages were extracted, excluding transition periods, and the average of two trials was used as the representative value. The force plates were used to determine the start and end of SLS, and a force of 20 N was used as the lower limit. The COP position was calculated based on three different coordinate systems, namely the Global, Pelvic, and FPA coordinate systems, with an origin at the ankle joint center. The Global coordinate system was based on the absolute coordinate system of the laboratory. In contrast, the Pelvic and FPA coordinate systems were defined based on the coordinate system with the sagittal axis of the pelvis segment and longitudinal axis of the foot segment, respectively, as the Y axis (Fig. 1). COP-X was the COP position in the medial–lateral direction from the origin, with the lateral direction indicating a positive value. Moreover, COP-Y was the COP position in the anterior–posterior direction from the origin, and the anterior direction indicates a positive value. For arch height and COP position, in addition to the measured value, normalized by foot length (for arch height and COP-Y) and foot width (for COP-X) were calculated.

In statistical analysis, the normality of the data was assessed by a Shapiro–Wilk test. Subsequently, repeated measurements of one-way analysis of variance and multiple comparisons (Bonferroni adjustment) were performed using SPSS statistics version 27 (IBM Corp, Armonk, NY, USA) to identify significant differences associated with FPA. Significance was determined when $p<0.05$ for all statistical tests.

RESULTS

Table 2 lists the mean and standard deviations of each measured value among the three FPA conditions. FPA was −1.7° ± 2.2°, 8.1° ± 2.2°, and 17.5° ± 2.5° for toe-in, neutral, and toe-out, respectively, and significant differences between each FPA condition were observed. Pelvis obliquity was controlled within 1° in all FPA conditions; however, a significant difference was observed between toe-in and toe-out. In addition, a significant difference was observed between each FPA condition in pelvic rotation. However, no significant differences were observed in external ankle valgus moment and arch height. In COP-X (medial–lateral position), a difference between each FPA condition in the Global and Pelvic coordinate systems was observed but not in the FPA coordinate system. In COP-Y (anterior–posterior position), similar trends were exhibited in all coordinate systems (Global, Pelvic, and FPA), and a significant difference was observed between toe-in and toe-out.

DISCUSSION

Herein, we show that COP displacement based on the laboratory coordinate system is involved in the mechanism linking alterations in FPA to changes in KAM. Essentially, alterations in the FPA were found to affect the medial–lateral position of

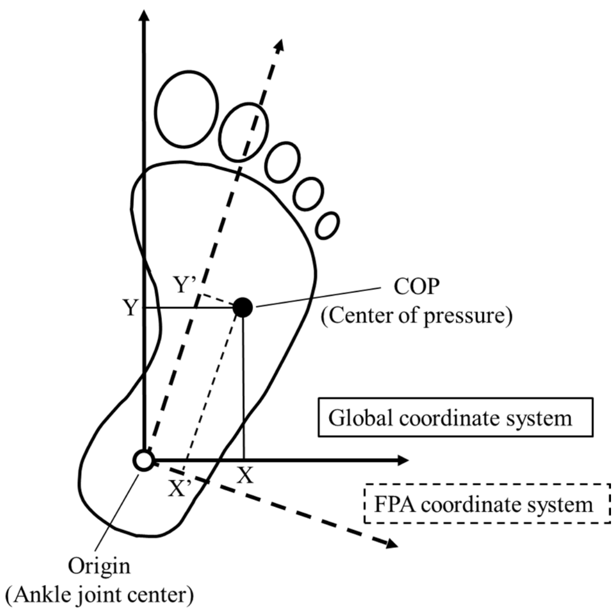

Fig. 1. Global and foot progression angle (FPA) coordinate systems.
The solid line indicates the global coordinate system based on the absolute coordinates of the laboratory. The dashed line indicates the FPA coordinate system based on the longitudinal axis of the foot segment. All coordinate systems have an origin at the ankle joint center. Center of pressure (COP)-X denotes the COP position in the medial-lateral direction from the origin, where (X) and (X') are the values in the Global and the FPA coordinate systems, respectively. COP-Y denotes the COP position in the anterior-posterior direction from the origin, where (Y) and (Y') are the values in the Global and the FPA coordinate systems, respectively.

Table 2. Comparison of each measured value among three foot progression angle (FPA) conditions

	Measured value			Normarized value (%)		
	Toe-in	Neutral	Toe-out	Toe-in	Neutral	Toe-out
Foot progression angle (deg)						
Abduction (+) / Adduction (−)	−1.7 ± 2.2[a]	8.1 ± 2.2	17.5 ± 2.5[a,b]			
Pelvis angles (deg)						
Anterior tilt (+) / Posterior tilt (−)	9.1 ± 4.2	9.0 ± 4.2	8.3 ± 4.5			
Contralateral obliquity (+) / Ipsilateral obliquity (−)	0.1 ± 1.6	−0.3 ± 1.8	−1.0 ± 1.6[b]			
Contralateral rotation (+) / Ipsilateral rotation (−)	−3.3 ± 3.0[a]	−1.3 ± 3.5	0.4 ± 3.6[a,b]			
External ankle eversion moment (Nmm/kg)	88.9 ± 22.4	85.2 ± 27.9	82.0 ± 28.5			
Arch height (mm)	72.4 ± 3.3	72.4 ± 3.3	72.1 ± 3.4	29.1 ± 1.4	29.1 ± 1.4	28.9 ± 1.4
COP-X (mm)						
Global coordinate system	−4.9 ± 7.9[a]	4.6 ± 6.3	14.6 ± 6.0[a,b]	−4.8 ± 7.7[a]	4.6 ± 6.3	14.5 ± 6.0[a,b]
Pelvis coordinate system	−1.6 ± 9.3[a]	5.6 ± 7.7	14.1 ± 7.3[a,b]	−1.5 ± 9.1[a]	5.6 ± 7.6	14.0 ± 7.3[a,b]
FPA coordinate system	−2.9 ± 5.9	−3.2 ± 5.5	−1.4 ± 6.0	−2.8 ± 5.7	−3.2 ± 5.4	−1.4 ± 5.9
COP-Y (mm)						
Global coordinate system	60.5 ± 9.9	56.2 ± 13.1	51.6 ± 13.4[b]	24.2 ± 3.6	22.6 ± 5.1	21.5 ± 5.1[a,b]
Pelvis coordinate system	60.4 ± 10.1	56.0 ± 13.1	51.5 ± 13.6[b]	24.2 ± 3.7	22.4 ± 5.1	20.6 ± 5.2[b]
FPA coordinate system	60.8 ± 10.0	56.4 ± 13.3	53.6 ± 13.7[b]	24.4 ± 3.7	22.6 ± 5.2	21.5 ± 5.3[b]

Mean ± Standard deviation. COP-X: Position of the COP in the medial-lateral direction. COP-Y: Position of the COP in the anterior-posterior direction. FPA: Foot progression angle; COP: Center of pressure. a: Significant difference compared to neutral, b: Significant difference compared to toe-in.

the COP on the frontal plane, thereby positioning the COP medially in the toe-in and laterally in the toe-out. Considering that the pelvic obliquity was controlled to within 1°, trunk movements did not affect COP position. Furthermore, as pelvic rotation exhibited differences in all FPA conditions, we considered the position of the COP based on the Pelvic coordinate system; nonetheless, the results were similar to those based on the Global coordinate system. Therefore, the change in the COP position was considered to be the result of the change in the direction of the foot based on the laboratory owing to FPA alteration.

Previous studies have predicted that the mechanism by which toe-out gait decreases KAM is the reduction of the lever arm; however, sufficient data supporting this claim have not been presented[5, 13)]. In this study, lateral displacement in COP position with toe-out based on the laboratory coordinate system is a factor that explains the reduction in lever arm. In contrast, the medial displacement in COP position owing to toe-in was a factor leading to the increase in lever arm, thus contradicting the results of the previous study[4)]. The decrease in KAM associated with toe-in gait is observed in the early stance phase, at which point the COP appears from the posterior position of the ankle joint. Therefore, medial displacement in the COP position was considered the result of COP displacement along the longitudinal axis of the foot segment. Moreover, considering that toe-in induces a medial shift in the knee joint center position[4)], whether the lever arm actually increases cannot be determined in this study.

The results of this study provide further findings. The alteration of FPA does not change the medial–lateral position of the COP within the plantar. In this study, FPA differences of 10° were observed between the toe-in, neutral, and toe-out cases. Therefore, sufficient medial–lateral position change of COP based on Global and Pelvic coordinate systems were provided. This FPA setup is general and provides sufficient biomechanical changes[9–11)]. Nonetheless, the results of this study reveal that the external ankle joint eversion moment and medial–lateral position of the COP within the plantar did not exhibit any change. As changes in COP position are closely related to muscle activity[14)], the alteration of FPA could result in unfavorable biomechanical changes in the ankle joint but did not preclude the practice of gait modification to alteration of FPA, given the results. Furthermore, we predicted that the difference in arch height would have different effects on both COP[15)] and KAM[16)], but no significant differences were observed between the three FPA conditions among the participants of this study.

Regarding the anterior–posterior position of COP, similar trends were exhibited regardless of the differences in coordinate system. Essentially, posterior displacement of the COP was observed in the toe-out condition compared with the toe-in condition. As the FPA was set to 0° at toe-in (actually −1.7° ± 2.2°), a posterior COP displacement associated with an increase in FPA was observed at toe-out. However, the position of the COP within the plantar was also displacement posteriorly, which suggests that a mechanism different from the position of the medial-lateral COP occurred.

In this study, we investigated the direct involvement of FPA on COP by controlling trunk movements. However, this study has a limitation corresponding to the selection of SLS, which is static motion. In general, numerous studies on FPA select gait as a motor task because FPA affects the early (approximately 25%) and late (approximately 75%) KAM in the stance phase[17)], during which sufficient plantar contact is not achieved. Therefore, it is highly likely that the COP position depends on the base of support, and consequently, we could not provide a full understanding of the effects of FPA on COP in this study. In summary, alteration of FPA during SLS affects the COP on the frontal plane but not the medial–lateral position of the COP within the plantar.

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All authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

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