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Original Article

The Forward Velocity of the Center of Pressure in the Midfoot is a Major Predictor of Gait Speed in Older Adults☆

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SUMMARY

Background: A better understanding of why gait speed declines with aging is necessary. Since the center of pressure (COP) controls the forward progression of the body during gait and the kinematic changes with aging are often observed during initial contact and toe-off phase, the forward COP velocities of these phases may have important roles for predicting gait speed.
Methods: Sixty-eight community dwelling older females (mean age 72.3 years) participated. The COP was measured using an F-scan pressure-sensitive insole system, and the anterior-posterior displacements versus time were quantified. The foot was divided into three regions (rear, mid, and forefoot), and the forward COP velocity was calculated at each region (Velocity 1, Velocity 2, and Velocity 3). Gait speed, double support phase (DSP), and cadence were also measured. Correlations and multiple regression analysis were performed.
Results: Gait speed was significantly associated with age ($r = -0.46$), DSP ($r = -0.51$), cadence ($r = 0.41$), Velocity 1 ($r = 0.29$), and Velocity 2 ($r = 0.61$). However, no correlation was found between Velocity 3 and gait speed. In multiple regression analysis using gait speed as a dependent variable, age, DSP, and Velocity 2 were significant predictors of gait speed, with Velocity 2 being the most significant predictor.
Conclusion: The COP velocity of the midfoot is an important factor for predicting gait speed, suggesting that the mobility of the COP during the single stance phase has a significant effect on gait speed in older adults.

1. Introduction

Although adequate gait speed is essential for older adults to maintain an independent and active life[1], it declines by 12–16% per decade after the age of 70 years[2]. Gait speed is well known as a good predictor of a wide range of outcomes, including falls[3], hospitalization[4], and survival[5] in older adults. Decreasing gait speed is a major public health problem for older adults and society; therefore, a better understanding of how aging affects gait speed is required.

Older adults, compared with young adults, walk slower with a shorter step length, longer double support phase (DSP), and less range of motion at the hip, knee, and ankle joints[6,7]. Kinematic analysis shows reduced ankle dorsiflexion during initial contact and reduced plantar flexion during the toe-off phase in older adults[8,9]. These kinematic reductions with aging are primarily caused by a reduction in distal muscles for power generation rather than in the proximal muscles. In particular, older adults exhibit a reduced ankle plantar flex power during gait[10]. Joint torque and joint power at the ankle are directly related to gait velocity[7,11].

The center of pressure (COP) on the plantar surface of the foot is defined as the point of location of the vertical ground reaction force vector[12]. The pathway of the COP during gait has been used to assess one's mode of locomotion and sense of balance[13]. Further,

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the velocity of the COP provides information about foot loading[14], gait pattern[15], and how gait changes[16]. Since the COP controls the forward progression of the whole body center of mass during gait[17], the forward velocity of the COP may potentially affect gait speed. Considering that the kinematic changes with aging are observed during the initial contact phase and the heel and toe-off phase[18], the forward COP velocities of these phases are more likely to affect the gait speed in older adults.

The location of the COP in the foot is considered to correspond to the phase during gait[17]. Specifically, the COP of the rear foot corresponds to the initial contact phase. Similarly, the COP of the midfoot and forefoot correspond with the mid-stance phase and heel and toe-off phase, respectively. Schmid et al[17] evaluated the COP displacement along the longitudinal axis of the foot versus time in amputees, and they were able to calculate the COP velocities of each region of the foot (i.e., the forefoot, midfoot, and rear-foot) based on the acquired COP data.

This study measured the COP velocity of each region of the foot during gait in elderly adults, according to the methods of the above-mentioned study[17]. The purpose of the study was to investigate which region's COP velocity is a crucial factor for predicting gait speed in older adults. We believe that this knowledge may be helpful for better understanding how aging affects gait speed. Since kinematic changes with aging are often observed during the initial contact and toe-off phase[18], we hypothesized that the COP velocities of the rear-foot and forefoot play important roles in predicting gait speed in older adults.

2. Methods

2.1. Participants

Sixty-eight community dwelling adults participated in the study. The participants were recruited through local senior centers and local newspaper advertisements. The inclusion criteria were female, aged ≥65 years, the ability to walk 10 m, and the ability to understand and follow instructions. The Human Subjects Committee of Osaka Prefecture University, Habikino City, Japan approved the study, and written informed consent was obtained from all participants.

2.2. Measurements

Gait speed was measured using a stopwatch while participants walked a 10 m walkway in the laboratory. The initial and final 2.5 m sections were not timed to allow for acceleration and deceleration. The participants were instructed to walk at a comfortable and secure pace.

The F-scan system, version 5.23 (Nitta Corp., Osaka, Japan) was used to measure dynamic foot pressure. The reliability of the F-scan system has been well documented by previous studies[13,19]. The foot pressure was recorded at 50 Hz with a pressure-sensitive insole, which consisted of a 0.15 mm thick sensor and 960 sensing locations (4 cells/cm^2). Participants wore shoes with the insole, and amplifiers were placed on both lateral sides of their ankles. The coordinates of the COP were calculated using the F-scan software. Three practice trials were performed to allow individuals to familiarize themselves with the procedure, and data were collected in four subsequent trials. Only the data obtained during the final trial were used in the analysis.

2.3. Data processing

With each participant, the middle, consecutive six steps were retained for subsequent analysis to exclude the gait initiation and termination. We analyzed 408 steps from 68 participants. Fig. 1 shows a typical COP trajectory (X and Y) of the foot. Velocity and acceleration of the COP were calculated based on the coordinates of the COP position. The stance phase was divided into three phases by the following points: (1) P1 corresponded to the point of maximum acceleration; and (2) P2 referred to the maximum deceleration[17]. In Phase 1 from the heel contact to P1, the COP was located in the rear foot. In Phase 2 from P1 to P2, the COP was located in the midfoot. Finally, in Phase 3 from P2 to toe-off, the COP was located in the forefoot. The mean velocity of the longitudinal displacement was calculated during Phase 1 and defined as Velocity 1. Velocity 2 and Velocity 3 were defined accordingly. Thus, Velocity 1, Velocity 2, and Velocity 3 represented the COP velocity of the rear-foot, midfoot, and forefoot, respectively. Cadence and DSP were also calculated using this F-scan data.

2.4. Statistical analysis

First, descriptive statistics for the participants' characteristics and gait variables were calculated. Pearson's correlation coefficients were used to assess the relationships between the gait variables (gait speed, cadence, and DSP) and the COP velocities (Velocity 1, Velocity 2, and Velocity 3). Multiple linear regression analysis with forced entry was conducted to determine which independent variables were significant predictors of gait speed. All analyses were performed using SPSS, version 20 (SPSS Inc., Chicago, IL, USA), and $p < 0.05$ were considered significant.

3. Results

The characteristics of the participants are shown in Table 1. The mean age was 72.3 ± 4.3 years, and the mean gait speed was 134.7 ± 17.1 cm/s.

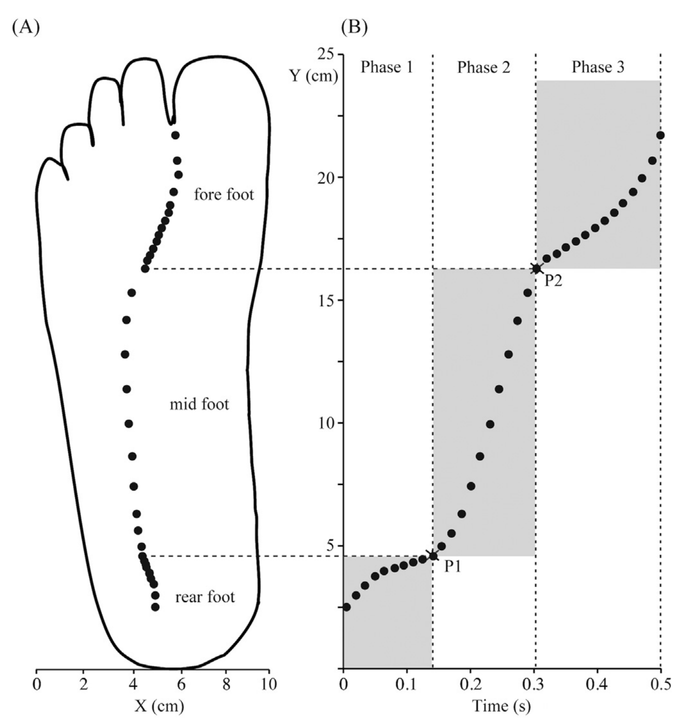

Fig. 1. A typical trajectory of the center of pressure (COP) in the foot. (A) The COP trajectory in X–Y with respect to the foot. (B) The COP movement along the Y-axis versus time. P1 corresponds to the point of maximum acceleration in the rear foot. P2 corresponds to the point of maximum deceleration in the forefoot.

Table 1
Characteristics of the participants ($n = 68$).

Characteristics	Value	Range
Physical characteristics		
Age (y)	72.3 ± 4.3	65–83
Height (cm)	150.3 ± 4.1	142.2–162.2
Weight (kg)	50.4 ± 6.1	31.3–63.1
Body mass index (kg/m^2)	22.3 ± 2.6	15.2–29.5
Gait variables		
Gait speed (cm/s)	134.7 ± 17.1	100.0–170.0
Double support phase (%)	15.8 ± 3.2	7.9–24.0
Step length (cm)	58.1 ± 6.0	45.2–73.2
Cadence (steps/min)	124.8 ± 11.2	102.9–150.0
COP velocity		
Velocity 1 (cm/s)	26.9 ± 8.8	11.9–50.2
Velocity 2 (cm/s)	83.0 ± 33.1	36.5–194.7
Velocity 3 (cm/s)	20.9 ± 5.3	10.1–32.0

COP = center of pressure.

Pearson's correlation coefficients between gait variables and participant characteristics are presented in Table 2. Of note, the gait speed was moderately correlated with velocity 2 ($r = 0.61$, $p < 0.01$) and had a low correlation with Velocity 1 ($r = 0.29$, $p < 0.05$); there was no significant correlation with Velocity 3 (Fig. 2). Additionally, gait speed was associated with cadence and DSP.

Multiple liner regression analysis with forced entry was performed with gait speed as a dependent variable, and it was performed with age, cadence, DSP, Velocity 1, Velocity 2, and Velocity 3 as independent variables (Table 3). The independent variables accounted for 52% of the variability in gait speed. Age, DSP, and Velocity 2 were significant predictors for gait speed, with Velocity 2 ($\beta = 0.45$) being more significant than age ($\beta = -0.31$) and DSP ($\beta = -0.26$).

4. Discussion

The major finding of this study was that the COP velocities of the midfoot and rear-foot have a significant correlation with gait speed, with the midfoot more closely correlated than the rear-foot. Furthermore, the COP velocity of the midfoot has a greater effect on variance in gait speed than the other factors that also affect gait speed, such as age, cadence, and DSP. These findings indicate that the COP velocity of the midfoot has a significant role in predicting gait speed in older adults.

The COP controls the forward progression of the body during gait[17]. The period of the COP in the midfoot almost corresponds with the mid-stance phase, and the mid-stance phase is equivalent to the single stance phase[20]. Forward progression during gait is produced primarily by the ankle plantar flexors, and these muscles produce nearly all the support during the single stance phase[21]. Change in gait pattern with aging is caused by decreased power at the ankle joint[22], and the ankle joint power is directly related to gait velocity[7,11]. Considering these studies and the data from the present study, it is reasonable to assume that the ankle plantar power during the mid-stance phase may define the COP velocity of midfoot in the elderly, and the COP velocity of the midfoot may have an effect on gait speed. Additionally, since each region of the foot is defined by the maximum acceleration and deceleration of COP[17], the COP velocity of the midfoot is a region in which the magnitude of the velocity change is at a maximum. It is also possible that a smooth COP velocity change may have some influence on gait speed.

With aging, there are several changes in gait characteristics of the joint kinematics and kinetics. During the heel strike phase, older adults have less ankle dorsiflexion angle[8], which is interpreted as a tendency for a flat-footed landing[18]. During the late stance phase, older adults have a reduced ankle plantar flexion angle and lower ankle plantar flexor power[9]. Based on these studies, we presume that these changes may affect the reduction in the COP velocities of the rear- and forefoot, and we hypothesized that these velocities would be important for predicting gait speed in the elderly. Although the COP velocity of the rear-foot was significantly related to gait speed, no correlation was found between the COP velocity of the forefoot and gait speed. There are two possible reasons for this discrepancy. First, the opposite leg may have affected the result. Since the timing of the COP in the forefoot is in accordance with the opposite leg during the heel strike phase, the opposite leg may have more influence on gait speed during that phase. Second, the deformities of the forefoot may affect the results. Foot problems are reported by ~30% of community dwelling older people[23], and 60% of these problems are localized in the forefoot[24]. Since older adults with deformities of the forefoot display a difference in the COP trajectory[25], the COP velocity of the forefoot may be affected by the deformities, and therefore may have no correlation with gait speed.

The present study has several potential limitations. First, since the participants were female and independent community dwellers, it is not clear whether these findings can be generalized to the male or frail populations. Second, the COP velocities of young adults were not measured. Therefore, it is not certain whether these findings are specific characteristics of older adults. Further research is required to investigate the COP velocity of the same foot regions in males, young adults, and frail older adults.

In conclusion, the COP velocity of the midfoot explained much of the variance in gait speed in older adults. Since the stability during the single stance phase is a key element of safe walking[26], much attention has been paid to the stability of the stance leg in elderly gait. However, the present study demonstrates the importance of the COP velocity of the mid-stance for gait speed in older adults. This finding suggests that not only stability, but also the mobility

Table 2
Correlations between gait variables and center of pressure (COP) velocities.

	Gait speed	Age	DSP	Cadence	Velocity 1	Velocity 2	Velocity 3
Gait speed	–	−0.46**	−0.51**	0.41**	0.29*	0.61**	−0.28
Age (y)		–	0.27*	−0.25*	−0.04	−0.17	−0.06
DSP			–	−0.42**	−0.26*	−0.36**	0.17
Cadence				–	0.34**	0.51**	0.05
Velocity 1					–	0.28*	−0.48**
Velocity 2						–	−0.05
Velocity 3							–

**$p < 0.01$.
*$p < 0.05$.
DSP = double support phase.

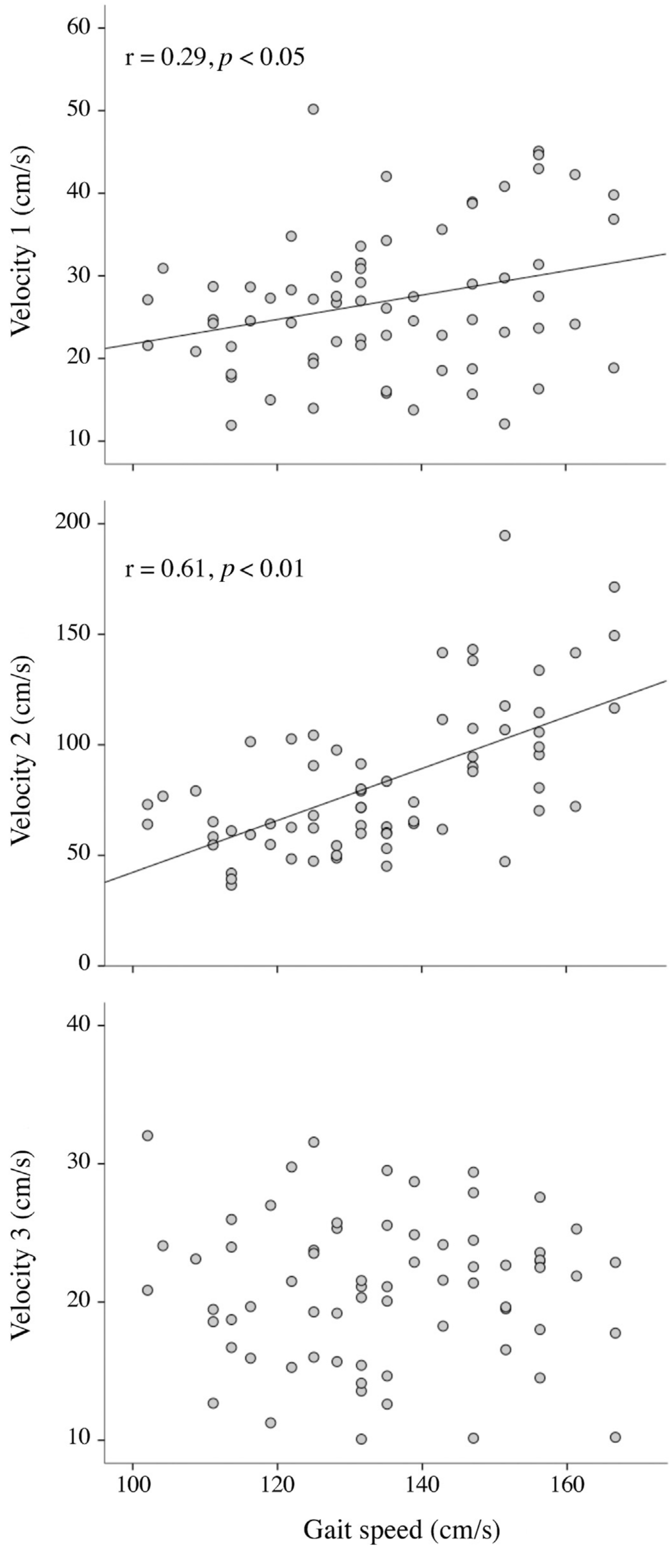

Fig. 2. The associations between the center of pressure (COP) velocities of each region of the foot and gait speed. Velocity 1, the COP velocity of the rear-foot; Velocity 2, the COP velocity of the midfoot; and Velocity 3, the COP velocity of the forefoot.

during the stance phase are required to maintain gait speed. Therefore, it may be necessary to emphasize the mobility of the stance leg during the stance phase, especially in a single stance phase, for preventing a decrease in gait speed.

Table 3
Results of multiple regression analysis with gait speed as a dependent variable.

Independent variable	β	SE	Adjusted β	p
Age (y)	−0.012	0.004	−0.312	0.001
BMI	−0.002	0.006	−0.030	0.757
Cadence	−0.001	0.002	−0.058	0.590
DSP	−0.014	0.006	−0.257	0.016
Velocity 1	0.003	0.002	0.146	0.176
Velocity 2	0.002	0.001	0.447	< 0.001
Velocity 3	0.003	0.003	0.088	0.385

R = 0.76, $R^2 = 0.57$, adjusted $R^2 = 0.52$.
BMI = body mass index; DSP = double support phase.

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