

Clinical Study

Abnormalities of the First Three Steps of Gait Initiation in Patients with Parkinson's Disease with Freezing of Gait

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The purpose of this study was to investigate abnormalities of the first three steps of gait initiation in patients with Parkinson's disease (PD) with freezing of gait (FOG). Ten PD patients with FOG and 10 age-matched healthy controls performed self-generated gait initiation. The center of pressure (COP), heel contact positions, and spatiotemporal parameters were estimated from the vertical pressures on the surface of the force platform. The initial swing side of gait initiation was consistent among the trials in healthy controls but not among the trials in PD patients. The COP and the heel contact position deviated to the initial swing side during the first step, and the COP passed medial to each heel contact position during the first two steps in PD patients. Medial deviation of the COP from the first heel contact position had significant correlation with FOG questionnaire item 5. These findings indicate that weight shifting between the legs is abnormal and that medial deviation of the COP from the first heel contact position sensitively reflects the severity of FOG during the first three steps of gait initiation in PD patients with FOG.

1. Introduction

Disturbance of gait initiation is common in patients with Parkinson's disease (PD) [1–9]. In particular, the postural phase, defined as the phase between the onset of weight shifting to the initial swing side and the onset of the heel off in the initial swing limb, is abnormal in PD patients [1–9]. Duration of the postural phase is prolonged [2, 4, 5]. The displacement of the center of pressure (COP) [5–8] and motoneuron pool excitability of the soleus muscle [9] are abnormal in this phase. Furthermore, electromyographic activities in the tibialis anterior muscle, vastus lateralis muscle, and gastrocnemius muscle are decreased in this phase [2]. The decreased step length during gait initiation [2, 5, 6] may reflect some of these abnormalities in the postural phase.

Gait abnormalities in PD patients were reported not only during gait initiation, but also during steady-state gait [10–14]. Step length and step velocity are reduced [10–13],

double limb support duration is prolonged [10–13], and stride-to-stride variability of gait cycle timing is increased [13]. Furthermore, movement amplitude of the legs and pelvis and the push-off peak of the vertical ground reaction force are reduced [11, 14].

Given the existing findings about gait abnormality in PD patients, we hypothesized that the transition phase between gait initiation and steady-state gait may also be abnormal in PD patients. This transition phase was investigated in a previous study [1]; however, the study was descriptive rather than a quantitative investigation. In the present study, we made a quantitative investigation of the transition phase between gait initiation and steady-state gait in PD patients. Two or three steps are necessary in the transition between gait initiation and steady-state gait in healthy humans [15]. Therefore, we measured kinesiological parameters of the first three steps of gait initiation in the present study.

Freezing of gait (FOG) is a symptom in which patients suddenly become unable to start walking or to continue

moving forward, and sometimes, it appears during gait initiation [16, 17]. Start hesitation, which is a common form of FOG, occurs in 4% of PD patients during the “ON” state and in 23% of PD patients during the “OFF” state [16]. FOG affects steady-state gait patterns. For example, stride time variability and stride time asymmetry in PD patients with FOG is higher than those in PD patients without FOG [18, 19], and the step length in PD patients with FOG is shorter than that in PD patients without FOG during treadmill walking [20]. Before the occurrence of freezing during steady-state gait, reduced step length and sequence effect, increased cadence, and premature timing of tibialis anterior muscle and gastrocnemius muscle are observed [21–23]. According to these findings, abnormality of gait pattern in the transition phase between gait initiation and steady-state gait may be prominent in PD patients with FOG. Therefore, the present study was conducted to investigate abnormality of the first three steps of gait initiation in PD patients with FOG.

2. Methods

2.1. Subjects. Ten PD patients, aged 63–78 years, and 10 age-matched healthy controls, aged 65–76 years, participated in this study. The PD patients were able to walk independently at least 10 m without assistive devices. The 6 male and 4 female subjects ranged in height from 1.42 m to 1.73 m. The healthy controls, 4 males and 6 females, ranged in height from 1.50 m to 1.69 m. There was no significant difference in age ($P = 0.16$) or height ($P = 0.58$) between the groups by unpaired t -test. Before beginning the experiment, the severity of FOG was assessed by a freezing of gait questionnaire (FOGQ) [24]. PD patients with FOGQ item 3 score >0 were included in the experiment, because a recent study reported that this criterion is a valid indicator to distinguish between PD patients with FOG and those without FOG [25].

Patient characteristics are shown in Table 1. All of the PD patients were being treated with stable doses of anti-Parkinsonian medications. The FOGQ total score ranged from 3 to 22. The score for FOGQ item 3, which asks about the unique experience of the feet getting glued to the ground in different situations [24], ranged from 1 to 3, and the score for FOGQ item 5, which asks about the duration of start hesitation, ranged from 0 to 3. All the subjects gave written informed consent for study participation in accordance with the Helsinki Declaration. The experiment was approved by the ethical committee of Osaka Prefecture University.

2.2. Apparatus. Gait initiation was performed on a force platform (Zebris Medical GmbH, Isny, Germany) placed on the first 2.18 m of a 9-m-long walkway. The length was expected to be sufficient to record three steps of gait initiation. The width of the platform was 0.6 m. This platform recorded vertical pressure on the surface of the force platform each 0.75 cm^2 at a sampling rate of 100 Hz. The COP, heel contact positions, and spatiotemporal parameters were estimated from the vertical pressures.

2.3. Experimental Protocol. All the experiments were conducted while the patients were in an “ON” state. The subjects stood barefoot on the force platform for a few seconds and initiated gait at their own pace. They continued to walk in the center of the walkway until the end of the walkway. They gazed at a target point 4 m beyond the end of the walkway. The target point indicated the approximate center of the walkway. One or two practice trials were performed before the experimental trials. The experimental trials were repeated until the subject successfully initiated gait by swinging the leg on either side 10 times. Only these 10 trials were included for data analysis.

2.4. COP Displacement. The COP trajectory between the onset of displacement of COP from quiet standing and the fourth toe off (the second toe off of the initial stance leg) was analyzed. The beginning of the COP trajectory was defined as zero along the anteroposterior and mediolateral axes. A positive COP value indicates the position anterior to zero along the anteroposterior axis and the deviation to the initial stance side in reference to zero along the mediolateral axis. The duration between the onset of COP displacement and the fourth toe off was defined as 100%. The COP trajectories were normalized according to this time scale, and the normalized COP trajectories were divided into the applicable 5% bins of the normalized time scale. Then, the COP was averaged for each 5% bin of the normalized time scale. In this way, we were able to estimate the average of twenty data points on the COP trajectory.

The 1st COP peak displacement was defined as the COP most deviated to the initial swing side before the first heel off (Figure 1). The 2nd COP peak displacement was defined as the COP most deviated to the initial stance side. The 3rd COP peak displacement was defined as the COP most deviated to the initial swing side after the 1st heel contact. The 4th COP peak displacement was defined as the COP most deviated to the initial stance side after the 2nd heel contact.

2.5. Spatiotemporal Parameters. The 1st step time was defined as the period between the onset of COP displacement and heel contact of the 1st step. The 2nd and 3rd step times were defined as the periods between heel contact in one foot and the next heel contact in the other foot. The single limb support (SLS) duration of each step was defined as the period between toe off and the next heel contact. The double limb support (DLS) duration was the period between the end of the SLS and the beginning of the next SLS. The DLS/cycle ratio was defined as the DLS duration divided by the sum of the SLS duration and the DLS duration (gait cycle duration). The step length was defined as the distance between the rear end of the right and left heels along the anteroposterior axis. The step width was defined as the distance between the rear end of the right and left heel centerlines along the mediolateral axis. The step velocity was expressed as the step length divided by the step time.

2.6. Heel Contact Position. The heel contact position along the anteroposterior axis was defined as the rear end of the

TABLE 1: Characteristics of PD patients.

Subject ID	Age (years)	Sex	H and Y stage	UPDRS-motor	LED (mg/day)	FOGQ-total	FOGQ-item 3	FOGQ-item 5
1	75	M	2	13	200	10	2	1
2	65	F	3	15	350	9	2	0
3	78	M	3	24	300	14	2	2
4	68	M	3	8	500	7	1	0
5	88	M	4	21	300	22	3	2
6	65	F	2	5	200	3	1	0
7	73	M	3	19	150	9	2	1
8	85	F	4	14	300	5	1	1
9	63	F	3	14	450	20	3	3
10	68	M	3	8	500	7	1	0

M: male, F: female; LED: levodopa equivalent dose; FOGQ: freezing of gait questionnaire.

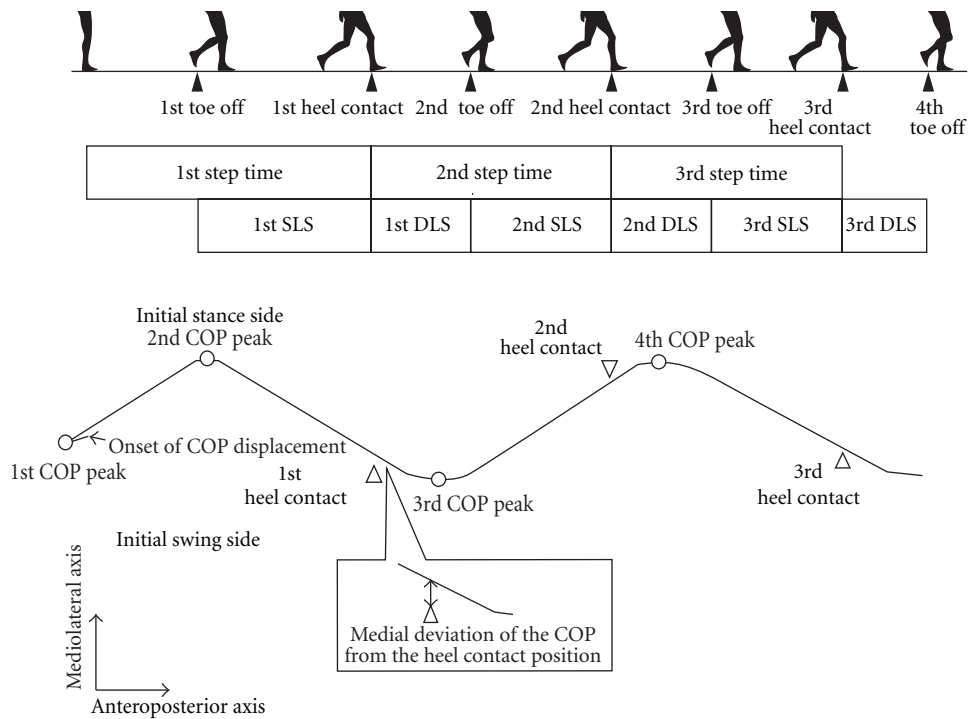


FIGURE 1: Spatiotemporal and kinesiological parameters. A trace in the middle of the figure indicates the COP trajectory. Open circles indicate COP peaks. Open triangles indicate heel contact positions.

heel. The heel contact position along the mediolateral axis was defined as the heel centerline. The amount of medial deviation of the COP from the heel contact position was also estimated. A positive value denoted medial deviation of the COP from the heel contact position, while a negative value denoted lateral deviation of the COP from the heel contact position.

2.7. Statistical Analysis. Statistical tests were performed using SPSS 14.0 for Windows, SPSS Japan, Inc. Unpaired t-tests were conducted to examine the difference in each variable between the PD and healthy groups. Spearman's rank

correlation coefficient was estimated between the FOGQ item 5 score, which reflects the severity of FOG during gait initiation, and gait parameters. The alpha level was 0.05. Data were presented as the mean values and standard error of the mean (mean (SEM)).

3. Results

3.1. General Features. All subjects were able to initiate gait without assistance. The first three steps were completely within the force platform in all trials of all subjects. The initial swing side was consistent throughout the trials in 9

out of 10 healthy controls. In contrast, the initial swing side was not consistent between the trials in PD patients; only 3 PD patients initiated gait with the same leg in all trials.

3.2. Spatiotemporal Parameters. As shown in Table 2, step velocity and step length of the first three steps in PD patients were significantly smaller than those in healthy controls ($P < 0.05$). The step width was not significantly different between the groups. The 1st step time in PD patients was significantly longer than that in healthy controls ($P < 0.05$). However, the 2nd and 3rd step times were not significantly different between the groups. The 1st and 2nd DLS/Cycle ratios in PD patients were significantly larger than those in healthy controls ($P < 0.05$).

3.3. COP Displacement. The COP trajectory in PD patients tended to deviate to the posterior side and to the initial swing side as compared to that in healthy controls (Figure 2). The 1st COP peak displacement along the anteroposterior axis in PD patients was significantly smaller than that in healthy controls ($P < 0.05$). The 2nd to 4th COP peak displacements along the anteroposterior axis in PD patients were significantly posterior to those in healthy controls ($P < 0.05$). The 2nd to 4th COP peaks along the mediolateral axis in PD patients tended to deviate to the initial swing side as compared to those in healthy controls. We noted in particular that the deviation of the 3rd COP peak displacement along the mediolateral axis was significantly different between the groups, as shown in Figure 3 ($P < 0.05$).

3.4. Heel Contact Position. The heel contact positions of the first three steps in PD patients tended to deviate to the posterior side and to the initial swing side in comparison with those in healthy controls (Figure 2). The 1st to 3rd heel contact positions along the anteroposterior axis in PD patients were significantly posterior compared to those in healthy controls ($P < 0.05$). As shown in Figure 4, the 1st and 3rd heel contact positions along the mediolateral axis in PD patients significantly deviated to the initial swing side, as compared to those in healthy controls ($P < 0.05$). The 2nd heel contact position tended to deviate toward the initial swing side in PD patients as compared to healthy controls although the deviation was not significant between the groups.

3.5. Medial Deviation of COP from the Heel Contact Position. The COP trajectory in PD patients passed medial to each heel contact position during the first three steps, as compared to healthy controls (Figure 2). As shown in Figure 5, the amount of medial deviation of the COP from the 1st heel contact position and that from the 2nd heel contact position in PD patients were significantly larger than those in healthy controls ($P < 0.05$).

3.6. Correlation between the FOGQ Item 5 Score and Gait Parameters. Step length and step velocity had a negative and significant correlation with the FOGQ item 5 score during the first three steps of gait initiation in PD patients

TABLE 2: Spatiotemporal parameters.

	PD	Healthy	<i>P</i> values
Step length (cm)			
1st	38.0 (3.8)	53.8 (1.5)	* <0.05
2nd	40.1 (3.6)	56.1 (1.1)	* <0.05
3rd	44.9 (3.9)	58.7 (1.0)	* <0.05
Step width (cm)			
1st	8.5 (0.9)	7.2 (1.0)	0.35
2nd	7.8 (1.4)	7.7 (0.9)	0.94
3rd	7.8 (1.3)	7.3 (0.9)	0.76
Step time (s)			
1st	1.14 (0.06)	0.98 (0.02)	* <0.05
2nd	0.63 (0.03)	0.61 (0.01)	0.62
3rd	0.54 (0.02)	0.53 (0.01)	0.55
Step velocity (m/min)			
1st	22.0 (2.4)	32.6 (0.7)	* <0.05
2nd	39.4 (3.8)	54.3 (1.7)	* <0.05
3rd	50.3 (4.1)	66.0 (1.8)	* <0.05
DLS/Cycle ratio			
1st	0.38 (0.03)	0.32 (0.01)	* <0.05
2nd	0.31 (0.02)	0.27 (0.01)	* <0.05
3rd	0.30 (0.03)	0.26 (0.01)	0.15

Mean (SEM).

Asterisks indicate significant difference between the groups.

($P < 0.05$), and the DLS/cycle ratio had a positive and significant correlation with the FOGQ item 5 score during the first three steps of gait initiation in PD patients ($P < 0.05$). The amount of medial deviation of the COP from the 1st heel contact position had positive and significant correlation with the FOGQ item 5 score ($P < 0.05$). In contrast, step width, step time, and COP peak displacements along the mediolateral axis did not have significant correlation with the FOGQ item 5 score.

4. Discussion

4.1. Spatiotemporal Parameters. Step length and step velocity were decreased during the first three steps of gait initiation in PD patients with FOG. The decrease in step length should be the cause of the decreased COP displacement along the anteroposterior axis. Decreased step length and step velocity during the first step of gait initiation in these patients have been reported [2, 5–7], as has a decrease in the step length of the second step [4]. These decreases are present not only during gait initiation but also during steady-state gait [10–13]. Accordingly, the decrease in step length and that in step velocity are probably not specific characteristics of the transition phase of gait initiation but general characteristics of all the phases of gait manifested as a shuffling gait.

4.2. COP Peak Displacement and Heel Contact Position. The 1st COP peak along the anteroposterior axis, reflecting backward deviation of the COP before the initial heel off of gait initiation, was found to be decreased, which was

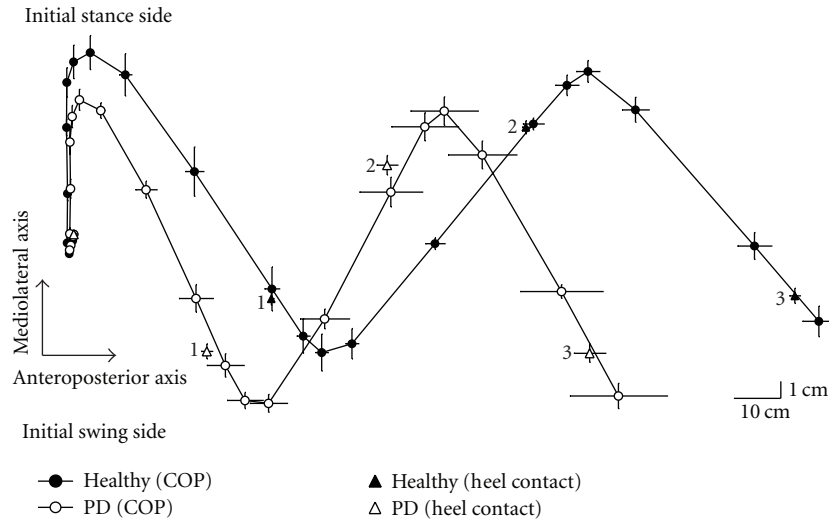


FIGURE 2: Averaged COP trajectory and heel contact position between the onset of COP displacement and the 4th toe off. Circles indicate the average of the normalized COPs. Triangles indicate the average of the normalized heel contact positions. Data points indicate the mean, and error bars indicate standard errors of the mean.

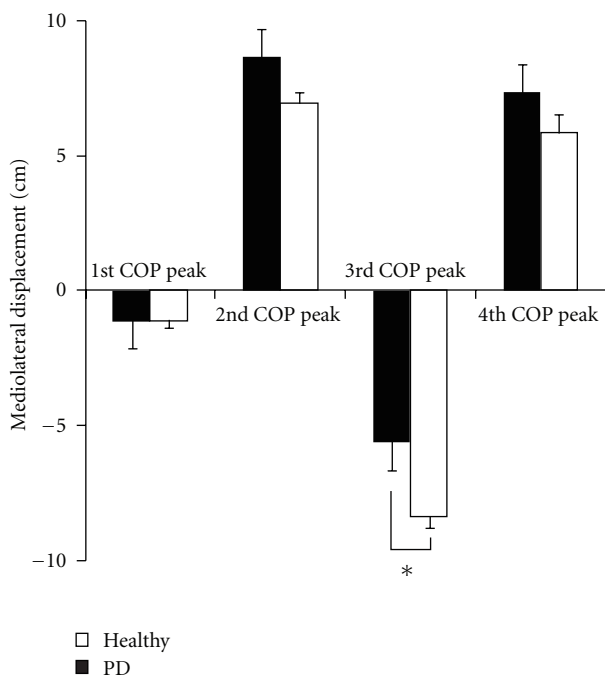


FIGURE 3: Mediolateral displacement of COP peaks. Data columns indicate the mean, and error bars indicate standard errors of the mean. An asterisk indicates a significant difference between the groups ($P < 0.05$).

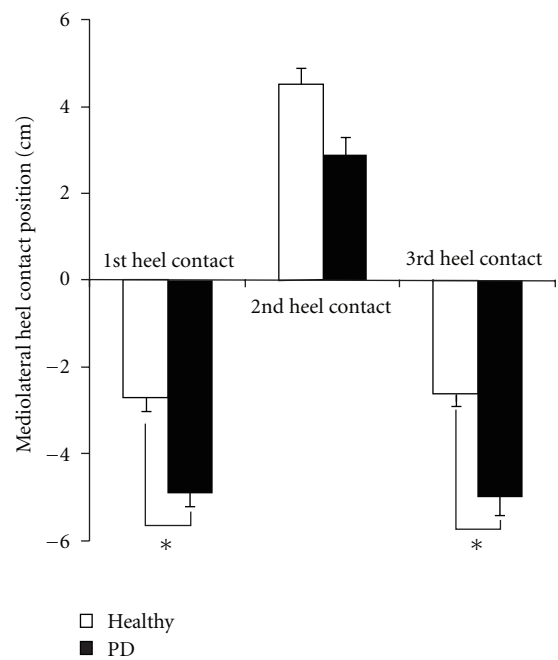


FIGURE 4: Mediolateral heel contact positions. Data columns indicate the mean, and error bars indicate standard errors of the mean. Asterisks indicate a significant difference between the groups ($P < 0.05$).

consistent with previous studies [5–8]. This finding should reflect abnormalities of the postural phase in PD patients [1–9]. The COP shifts backward and toward the swing limb during the postural phase. Furthermore, the 1st step time, which involves the duration of postural phase, was prolonged in PD patients with FOG, which was also consistent with previous findings [2, 4, 5]. Abnormality of the postural phase

should be mostly derived from impairment of the anticipatory postural adjustment (APA). The APA is impaired during gait initiation [5–8], before protective steps induced by a forward loss of balance [26], or during voluntary steps in PD patients [27], indicating that the APA occurs during the postural phase. Therefore, the prolongation of the 1st step time and the decreased 1st COP peak along the

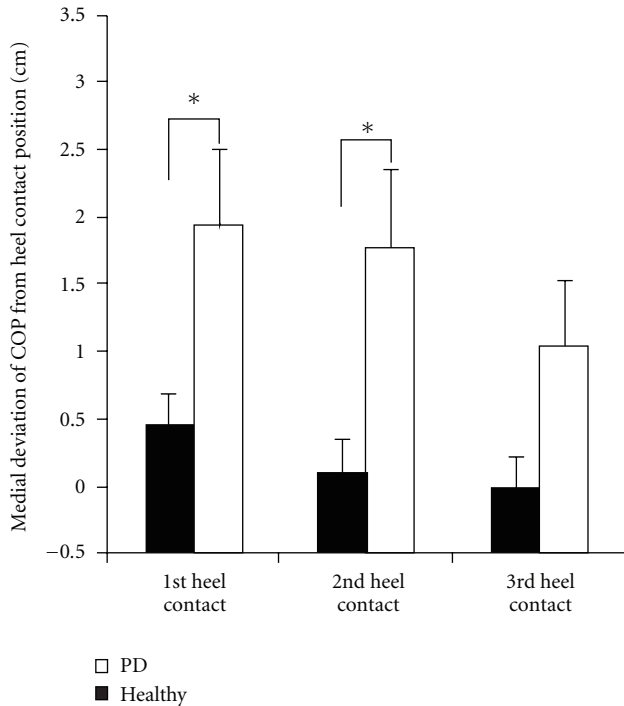


FIGURE 5: Medial deviation of the COP from the heel contact position. Data columns indicate the mean, and error bars indicate standard errors of the mean. Asterisks indicate a significant difference between the groups ($P < 0.05$).

anteroposterior axis observed in the present study should be related to impairment of the APA during gait initiation.

The 3rd COP peak displacement along the mediolateral axis in PD patients with FOG was significantly larger than that in healthy controls. This finding was associated with the significant deviation of the 1st heel contact position to the initial swing side in PD patients with FOG, compared to that in healthy controls. Such displacement should not be due to beginning to move in the wrong direction, because the subjects were instructed to walk toward a target point indicating the center of the walkway. Step width was not the cause of the displacement, because no significant difference in the step width was found between the groups throughout all the phases.

Insufficient weight shifting to the initial stance side immediately after the initial toe off may be related to the displacement. That is, a small weight shift to the initial stance side followed by normal weight shifting to the initial swing side resulted in abnormally large shifting of the COP to the initial swing side with reference to the zero position of the COP. A smaller tendency of the 2nd COP peak displacement to the initial stance side in PD patients with FOG supports this assumption. Another possible explanation is impaired braking of weight shifting to the initial swing side. Active braking of the center of gravity immediately before the first foot-contact of the initial swing limb during gait initiation is impaired in PD patients [28]. This impairment may have resulted in excessive weight shifting to the initial swing side without sufficient braking against the weight shift immediately before the first heel contact.

Not only the 1st heel contact position but also the 3rd heel contact position significantly deviated to the initial swing side. This finding indicates that the deviation of the COP to the initial swing side affected subsequent heel contact positions. It is not certain that this effect continues after the transition phase between gait initiation and steady-state gait, but it is certain that this deviation originates with the first step of gait initiation. Therefore, an increase in the 3rd COP peak displacement along the mediolateral axis should represent the abnormality specific to the transition phase between gait initiation and steady-state gait in PD patients with FOG.

4.3. Medial Deviation of COP from the Heel Contact Position. The COP trajectory in PD patients with FOG was significantly medial against the heel contact positions during the first two steps compared to that in healthy controls. This may be explained by the prolonged duration of double limb support in these patients. The DLS/cycle ratio was significantly larger in PD patients with FOG during the first two steps of gait initiation. This finding indicates that the tracing leg tends to remain on the ground even after the heel of the leading leg contacts the ground, which means that even when the heel contacts the ground, a certain amount of weight is still on the other limb. This finding indicates that a certain amount of weight remains on the tracing stance leg contralateral to the heel contact side. This delayed heel off in the tracing leg, and resulted in prolonged double limb support duration. Medial deviation of the COP from the 1st and 2nd heel contact position appears to specifically represent abnormality of the transition phase between gait initiation and steady-state gait in PD patients with FOG, because this abnormality was no longer present after the 2nd step of heel contact.

4.4. Correlation between the FOGQ Item 5 Score and Gait Parameters. Step length, step velocity, and the duration of double limb support had significant correlations with the FOGQ item 5 score in PD patients. The negative correlation of step length with FOG severity was consistent with a previous finding that step length in PD patients with FOG was shorter than that in PD patients without FOG during treadmill steady-state walking [20]. Generally, step velocity depends on step length, indicating that the dependency of step velocity on FOG severity largely reflects the dependency of step length on FOG severity. The positive correlation between duration of double limb support and FOG severity was a novel finding. However, these significant correlations between spatiotemporal parameters and the FOGQ item 5 score were present throughout the first three steps of gait initiation. Accordingly, these dependencies may continue even after the transition phase between gait initiation and steady-state gait. Therefore, these dependencies may not represent dependencies specific to the transition phase between gait initiation and steady-state gait.

Medial deviation of the COP from the first heel contact position during the first step of gait initiation was significantly correlated with the FOGQ item 5 score, but the correlation was not significant during the 2nd and 3rd steps.

These findings indicate that the medial deviation of the COP from the first heel contact position depends on the FOG severity, but this dependency is not sustained after the first step. Therefore, medial deviation of the COP from the first heel contact position should reflect the FOG severity specifically during gait initiation.

4.5. Trial-to-Trial Variability of the Initial Swing Side. The initial swing side of gait initiation was consistent throughout the trials in healthy controls, but it was not consistent between trials in PD patients with FOG. Such variability has also been reported during reaching-with-trunk movement. Trial-to-trial variability of the timing of arm-trunk coordination during reaching movements in PD patients is larger than that in healthy controls [29]. Furthermore, stride-to-stride variabilities of stride time, step time, swing time, and the duration of double limb support in PD patients are larger than those in healthy controls [13]. Accordingly, trial-to-trial variability of the initial swing side of gait initiation may reflect the variable motor pattern in PD patients.

4.6. Suggestions for Future Studies. In this study, we investigated the first three steps of gait initiation, but we did not experimentally confirm whether abnormalities were specifically present during gait initiation. Further studies investigating whether such abnormality is not present during steady-state gait are indispensable for testing whether the abnormalities are specifically present during gait initiation. On the other hand, PD patients with FOG are likely to show more advanced symptoms of their disease as comparing with PD patients without FOG. The present study included only PD patients with FOG. Accordingly, the present findings may be related to higher disease severity instead of the presence of FOG. Therefore, further studies in PD patients without FOG are needed to examine whether the findings of this study are specific to PD patients with FOG or applicable to PD patients in general.

5. Conclusions

The first three steps of gait initiation were found to be abnormal in PD patients with FOG. Major abnormalities include the deviation of the 3rd COP peak and the first heel contact position toward the initial swing side, indicating excessive weight shifting toward the initial swing side during the first step of gait initiation. Trial-to-trial variability of the initial swing side of gait initiation may reflect the variable motor pattern of gait initiation in PD patients. Our findings indicate that medial deviation of the COP from the first heel contact position reflects FOG severity specifically during gait initiation.

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