

ORIGINAL ARTICLE

Mediolateral Postural Control during Gait in Parkinson's Disease

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Objectives: Balance in the mediolateral direction is usually maintained in patients with early-stage Parkinson's disease (PD), but not in moderate-stage PD as revealed by the Tandem Gait Test. Although mediolateral postural control in PD patients remains controversial, previous studies have shown that the Tandem Gait Test may predict the risk of future falls in patients with PD. This study aimed to clarify postural control differences among PD patients with and without mediolateral balance impairments (MLBI: mediolateral balance impairments, nMLBI: non-mediolateral balance impairments, respectively) and healthy controls (HCs). **Methods:** We recruited 40 PD patients and 20 HCs. According to the Tandem Gait Test score, PD patients were divided into MLBI and nMLBI groups. Primary outcome measures were the ambulatory movement trajectory amplitude of the center of mass and its coefficient of variation (CV) during gait. **Results:** Mediolateral movement trajectory amplitudes and CV were not significantly different between the nMLBI group and HCs, whereas the mediolateral movement trajectory amplitude in the MLBI group was significantly higher than that in the nMLBI group. Moreover, the CV of the mediolateral movement trajectory amplitude in the MLBI group was significantly lower than that in the nMLBI group. The mediolateral movement trajectory amplitude was significantly correlated with the fall score. **Conclusions:** The current results suggest that PD patients with mediolateral balance impairments showed mediolateral postural sway during gait compared with PD patients without mediolateral balance impairments. It is necessary to focus on the instabilities in the mediolateral direction to avoid falls in PD patients.

Key Words: accelerometer; gait analysis; Parkinson's disease; postural balance; standing position

INTRODUCTION

It is well known that recurrent falls are common in people with Parkinson's disease (PD).¹⁾ The consequences are often fractures, fear of falling, decreased activity levels, and reduced quality of life.¹⁻³⁾ Therefore, it is important to prevent recurrent falls in PD patients, and it is necessary to identify predictors of recurrent falls. According to previous studies,

postural control deficits, freezing of gait (FOG), a previous history of falls, decreased leg strength, and cognitive impairment can be used as predictors of recurrent falls.⁴⁻⁷⁾

Regarding postural control deficits in the forward-backward direction, most falls in PD patients occur in the forward direction.⁸⁾ Postural control in the forward-backward direction such as rise to toe and compensatory stepping-backward are risk factors associated with recurrent falls.⁹⁾ Early-stage

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PD patients had smaller stability areas in the forward direction compared with those of healthy controls (HCs).^{10–12} Moreover, PD patients with FOG are predisposed to falling forwards and have a reduced ability to voluntarily lean forward compared with PD patients without FOG.^{9,13} Therefore, the center of pressure (COP) of PD patients with FOG shifts backward as a compensatory strategy to avoid forward falls.^{14,15} As a result, postural control in the forward–backward direction may be impaired from the early stage and may be one of the risk factors associated with recurrent falls.^{8–15}

Concerning postural control in the mediolateral direction, patients with moderate-stage PD fail to use side steps, the so-called step strategy, and fall during external perturbation tasks on a movable platform with lateral translation.¹⁶ As revealed by the Ten-Step Test, these patients also tend to frequently use side steps in tandem gait.¹⁷ The Tandem Gait Test is used to assess postural control in the mediolateral direction, and an inability to perform tandem gait predicts the risk of future falls in patients with moderate-stage PD.^{2,9} By contrast, 92% of early-stage PD patients take no side steps during tandem gait; that is, they do not need a step strategy.¹⁸ Moreover, PD patients in the early-to-moderate stage of disease show sufficient stability similar to that of HCs during weight-shifting tasks in the mediolateral direction.¹² Therefore, postural control in the mediolateral direction may differ according to the PD stage. It remains unknown whether postural control deficits in the mediolateral direction during weight-shifting tasks and gait are associated with PD severity and falls, although mediolateral postural sway in PD patients is associated with falls and disease severity in the static stance task.^{19,20}

Mediolateral postural control deficits during gait in other neurodegenerative diseases are often compensated for by increased step width to avoid falls in the mediolateral direction.²¹ Although postural control in the mediolateral direction in moderate-stage PD seems to be impaired, the step width in these patients is usually normal or narrow compared with those affected by other neurodegenerative diseases, such as idiopathic normal pressure hydrocephalus.²¹ Wide step widths are thought to prevent falling during gait by increasing the control over the center of mass (COM), which can result in movement limitations in the mediolateral direction. However, patients with moderate-stage PD cannot control the COM in the mediolateral direction and tend to fall because their step widths seem to be narrow. Therefore, adjusting trunk movement is important for PD patients to avoid falls in the mediolateral direction instead of adjusting step width.

To assess postural control deficits in the mediolateral direction during gait in patients with PD, few studies have reported trunk movement trajectory amplitudes using tri-axial accelerometers. A previous study has shown that the trunk movement trajectory amplitude and its coefficient of variation (CV) during gait are smaller in patients with PD than in those with other neurodegenerative diseases, such as spinocerebellar degeneration.²² To date, no study concerning these parameters has been conducted to compare PD patients with HCs or to categorize subgroups based on PD severity.²²

We hypothesized that patients with PD can be classified into two subgroups: those with mediolateral balance impairments (MLBI) and those without mediolateral balance impairments (nMLBI). We also considered that the MLBI group may show a narrower stability area in the mediolateral direction during a weight-shifting task, as well as higher mediolateral postural sway and CV during gait. Therefore, this study aimed to clarify the mediolateral postural control difference among three groups (HCs, MLBI, and nMLBI groups) during weight-shifting tasks and gait.

MATERIALS AND METHODS

Participants

For this study, 40 PD patients and 20 age-matched HCs were recruited. The study protocol was approved by the ethics boards of Hyogo Prefectural Rehabilitation Hospital at Nishi-Harima (Approval No. 1806) and Kobe University Graduate School of Health Sciences (Approval No. 794). All participants provided written informed consent according to the Declaration of Helsinki. The inclusion criteria were as follows: (1) a clinical diagnosis of idiopathic PD according to the United Kingdom Parkinson's Disease Society Brain Bank,²³ (2) age between 40 and 90 years, and (3) ability to walk for 10 m and tolerate a bipedal standing position for 2 min without assistance. The exclusion criteria were as follows: (1) presence of dementia as defined by a Mini-Mental State Examination (MMSE) score of 23 or less, (2) presence of neurological disease other than PD or musculoskeletal disease, (3) severe dyskinesia, and (4) severe “on/off” fluctuations. Demographic characteristics of HCs and PD patients were recorded as age, sex, height, weight, MMSE score, and Timed Up and Go (TUG) test time. Further disease-specific information was gathered for PD patients, including disease duration, Hoehn and Yahr stage (HY stage), the levodopa equivalent dose (LED),²⁴ Unified Parkinson's Disease Rating Scale (UPDRS) part III,²⁵ pull test score (defined as

UPDRS item 30), fall score (defined as UPDRS item 13), and Montreal Cognitive Assessment. All PD patients were evaluated in the “on” state of their medication.

Ten-Step Test

The Ten-Step Test was applied to all participants.^{17,18} They were allowed to visually explore a straight line on the floor and were then asked to take ten tandem steps along the line. The participants wore a belt with handles at their waist. An assessor behind the participant carefully monitored whether each step was on the line and whether the heel of one foot touched the toe of the other. When participants were unable to maintain their balance, the assessor supported the participants to prevent falls. This test was performed three times and was scored as follows: 0, no side steps; 1, a single side step; 2, multiple side steps; and 3, unable to take four consecutive steps.^{17,18} According to the mean score of the three trials, PD patients were classified as MLBI (score ≥ 1) or nMLBI (score < 1).

Gait Assessment Procedure

The primary outcome measures were ambulatory COM trajectory amplitude and its CV during gait at a comfortable speed assessed by a triaxial accelerometer (MG-M1100, LSI Medience, Tokyo, Japan).²⁶ This device was attached to the lower back at the L3 vertebra level (approximate center of mass) using a belt.²⁶ The participants were instructed to walk at a comfortable speed without walking aids or assistance. The walkway in this test was a 16-m straight path with a 3-m acceleration section and a 3-m deceleration section.²⁶ The acceleration signals were recorded every 10 ms and imported into a dedicated software application (MG1100-PC, Gait View, Tokyo, Japan). The movement trajectory amplitudes in the mediolateral (ML) and vertical (VT) directions were calculated for the double integral of the acceleration signals. In addition, the step stride and the movement trajectory amplitudes in the ML and VT directions were normalized according to participant height. The trajectory amplitude represents COM movement, and the CV was calculated as follows: (standard deviation of the movement trajectory amplitude / mean of the movement trajectory amplitude) $\times 100$.²⁶ This gait assessment was performed three times. Data are presented as the mean value of the three trials.

COP Analysis to Assess Postural Control

The secondary outcome measure was the COP analysis value in postural control tests performed on a force plate (MG-1120, Anima, Tokyo, Japan). Vertical forces were

recorded on the force plate at a sampling rate of 50 Hz. Participants were instructed to stand barefoot on the force platform with feet fixed at parallel taped lines (10 cm heel-to-heel distance) with arms alongside the body. Participants were instructed to fixate a marker 2 m in front of them at a height matched to their line of sight. The assessor stood behind the participant for safety. Postural control examinations consisting of two tasks were performed according to a previous study.¹² First, participants were instructed to stand in an upright position, and the COP trajectory was recorded for 30 s (quiescent standing test). Second, participants were instructed to lean maximally forward, backward, right, and left without moving their feet or bending their hips (voluntary four-directional leaning test). The participants were asked to maintain the maximum leaning posture without swaying, and the COP trajectory in each direction was recorded for 10 s. Before these trials, the participants practiced this test once to perform the aforementioned steps.

The locus length, sway area, and locus length per unit area were calculated using COP analysis.¹² In addition, the locus length and sway area were normalized according to participant height. In the voluntary four-directional leaning test, the mean values of the forward, backward, right, and left displacements were calculated. The stability range and area were calculated as follows: forward–backward stability range = (forward–backward moving distance / participant’s foot length) $\times 100$; right–left stability range = (right–left moving distance / participant’s feet width + 10 cm) $\times 100$; and stability area = (forward–backward stability range \times right–left stability range) / 100. Postural control examinations were performed twice. Data are presented as the mean value of two trials.

Statistical Analysis

Descriptive statistics were compared among the three groups. Normal distribution was assessed using the Shapiro–Wilk test. According to the results, a one-way analysis of variance (ANOVA) or Kruskal–Wallis test for continuous variables and Fisher’s exact test for categorical variables were used to compare the differences among the three groups. When a significant difference was observed, the Tukey–Kramer test or Steel–Dwass test was performed as a post-hoc analysis. Previous study has shown HY stage to be a confounding factor for the Ten-Step Test.^{17,18} Thus, an analysis of covariance (ANCOVA) with HY stage as a covariate was also performed to compare the differences between MLBI and nMLBI groups when normally distributed. Pearson’s correlation analysis was performed to analyze the

Table 1. Demographic characteristics in each group

	HCs (n=20)	nMLBI (n=26)	MLBI (n=14)	P-value	P-value HCs vs nMLBI	P-value HCs vs MLBI	P-value nMLBI vs MLBI
Age (years)	68.7 (5.7)	69.1 (6.4)	70.9 (4.6)	0.53 ^a	0.95 ^b	0.52 ^b	0.64 ^b
Sex (male/female)	8/12	11/15	9/5	0.38 ^c	-	-	-
Height (cm)	159.5 (10.7)	160.0 (10.7)	158.8 (7.6)	0.91 ^a	0.98 ^b	0.96 ^b	0.91 ^b
Weight (kg)	60.1 (13.8)	57.2 (11.4)	59.5 (8.4)	0.67 ^a	0.68 ^b	0.99 ^b	0.81 ^b
MMSE	29.1 (1.0)	28.6 (1.2)	28.2 (1.7)	0.24 ^d	0.35 ^e	0.28 ^e	0.90 ^e
TUG (s)	5.1 (0.6)	7.4 (1.9)	8.2 (1.9)	<0.001 ^d	<0.001 ^e	<0.001 ^e	0.38 ^e
Ten-Step Test score	0.2 (0.3)	0.2 (0.2)	1.5 (0.6)	<0.001 ^c	0.98 ^d	<0.001 ^d	<0.001 ^d
MOCA	-	26.0 (2.0)	25.2 (2.9)	0.28 ^f			
Disease duration (years)	-	7.0 (4.1)	9.5 (6.3)	0.15 ^f			
LED (mg)	-	738.8 (281.8)	694.5 (320.0)	0.65 ^f			
HY stage (2.0/2.5/3.0/3.5/4.0)	-	10/4/11/1/0	2/1/9/1/1	0.23 ^c			
UPDRS part III	-	21.0 (12.6)	19.2 (10.2)	0.67 ^g			
Pull test (UPDRS item 30)	-	0.88 (0.81)	1.21 (0.69)	0.20 ^g			
Fall score (UPDRS item 13)	-	0.1 (0.3)	0.6 (1.0)	0.022 ^g			

Data presented as mean (SD) or number.

^a One-way ANOVA; ^b Multiple comparison with Tukey's post-hoc test; ^c Fisher's exact test; ^d Kruskal-Wallis test; ^e Multiple comparison with Steel–Dwass post-hoc test; ^f Independent t-test; ^g Mann–Whitney U test. MOCA: Montreal Cognitive Assessment.

relationships between the fall score (UPDRS item 13) and gait assessment parameters. Statistical analyses were performed with R 2.8.1 at an α level of 0.05. Data were expressed as mean \pm standard deviation.

RESULTS

Participant Characteristics

Table 1 shows the demographic characteristics of HCs and PD patients. **Figure 1** shows the flowchart for the recruitment and allocation of HCs and PD patients. According to the score of the Ten-Step Test in PD patients, 14 were classified as MLBI (score ≥ 1) and 26 as nMLBI (score < 1). The participants' age, sex, height, weight, and MMSE score were comparable among the three groups. The mean TUG results in the nMLBI and MLBI groups were significantly higher than that of the HC group, whereas there was no significant difference between MLBI and nMLBI groups (HCs vs nMLBI: $P < 0.001$; HCs vs MLBI: $P < 0.001$; nMLBI vs MLBI: $P = 0.38$). The mean score of the Ten-Step Test for the MLBI group was significantly higher than those of the HC and nMLBI groups, but no significant difference was found between HCs and the nMLBI group (HCs vs nMLBI: $P = 0.98$; HCs vs MLBI: $P < 0.001$; nMLBI vs MLBI: $P < 0.001$). The mean fall score (UPDRS item 13) of the MLBI group was

significantly higher than that of the nMLBI group ($P = 0.022$), whereas other clinical parameters did not differ between these groups.

Gait Analysis

Table 2 shows the results of the gait analysis, covering gait velocity, step stride, VT movement trajectory amplitude, and the CV of the VT movement trajectory amplitude. The mean gait velocity in the MLBI group was slower than those of the HC and nMLBI groups (HCs vs MLBI: $P < 0.001$; nMLBI vs MLBI: $P = 0.033$), whereas there was no significant difference between the HC and nMLBI groups. The mean step stride of the MLBI group was significantly shorter than those of the HC and nMLBI groups (HCs vs MLBI: $P < 0.001$; nMLBI vs MLBI: $P = 0.007$). In addition, the mean step stride of the nMLBI group was significantly shorter than that in HCs ($P = 0.012$).

The mean VT movement trajectory amplitudes in the nMLBI and MLBI groups were significantly smaller than that in HCs (HCs vs nMLBI: $P = 0.016$; HCs vs MLBI: $P < 0.001$), whereas there was no significant difference between the nMLBI and MLBI groups. The CV of the VT movement trajectory amplitude in the MLBI group was significantly higher than that in HCs ($P = 0.021$). The CV of the VT movement trajectory amplitude in the nMLBI group was not sig-

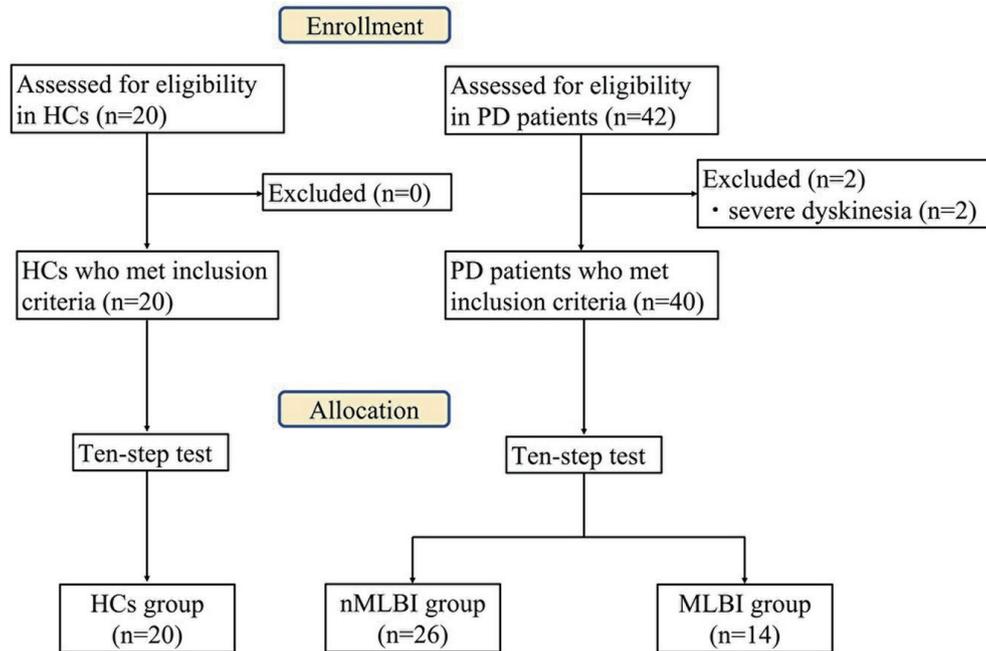


Fig. 1. Flowchart for the recruitment and allocation of HCs and PD patients.

Table 2. Gait analysis in each group

	HCs (n=20)	nMLBI (n=26)	MLBI (n=14)	P-value	P-value HCs vs nMLBI	P-value HCs vs MLBI	P-value nMLBI vs MLBI	Corrected P-value nMLBI vs MLBI
Gait velocity (m/s)	1.23 (0.17)	1.10 (0.20)	0.94 (0.18)	<0.001 ^a	0.076 ^b	<0.001 ^b	0.033 ^b	0.021 ^c
Step stride (m)	0.66 (0.06)	0.58 (0.10)	0.49 (0.07)	<0.001 ^a	0.012 ^b	<0.001 ^b	0.007 ^b	0.035 ^c
Movement trajectory amplitude VT (cm)	3.56 (0.64)	2.91 (0.89)	2.37 (0.64)	<0.001 ^a	0.016 ^b	<0.001 ^b	0.088 ^b	0.057 ^c
CV of movement trajectory amplitude VT (%)	7.96 (3.08)	11.48 (9.40)	11.77 (5.72)	0.031 ^d	0.15 ^e	0.021 ^e	0.82 ^e	NA

Data presented as mean (SD).

^a One-way ANOVA; ^b Multiple comparison with Tukey's post-hoc test; ^c One-way ANCOVA; ^d Kruskal-Wallis test; ^e Multiple comparison with Steel–Dwass post-hoc test. NA, not available.

nificantly different from those of the HC and MLBI groups.

Figure 2 shows the results of gait analysis for the ML movement trajectory amplitude and its CV. The MLBI group showed a significantly larger ML movement trajectory amplitude and a significantly lower CV than the HC and nMLBI groups, whereas the ML movement trajectory amplitude and its CV were not significantly different between the HC and nMLBI groups. In addition, use of HY stage as a covariate in ANCOVA did not influence the results of ML movement trajectory amplitude when compared between nMLBI and MLBI groups. Similarly, normalization according to par-

ticipant height did not influence the results of the step stride or the movement trajectory amplitudes in the ML and VT directions.

Table 3 shows the results of correlation analyses between the fall score (UPDRS item 13) and gait assessment parameters in PD patients. The ML movement trajectory amplitude was significantly correlated with the fall score (P=0.022), whereas no other gait assessment parameters showed significant correlations with the fall score of UPDRS.

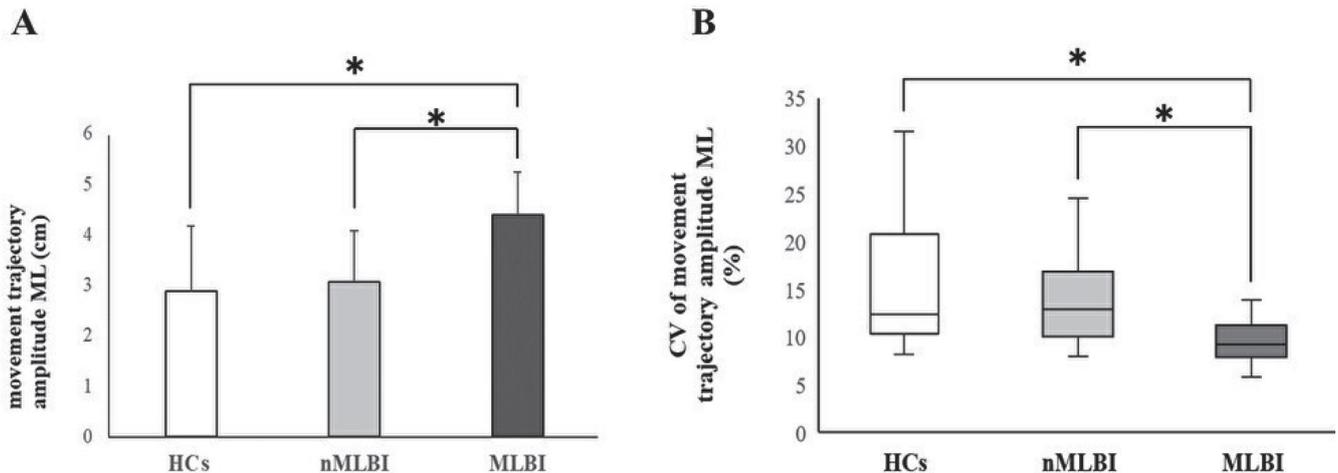


Fig. 2. (A) Movement trajectory amplitude in the ML direction for each group. Bars represent means and error bars represent standard deviations. (B) CV of movement trajectory amplitude in the ML direction for each group. Boxplots represent median, interquartile range, and range. Asterisks represent significant differences ($P < 0.05$).

COP Analysis for Quiescent Standing and the Voluntary Four-directional Leaning Test

Table 4 shows the COP values during postural control examinations. In the quiescent standing test, the sway area in the MLBI group was significantly more affected than that in HCs ($P=0.023$), whereas there was no significant difference in other parameters of each group. During the voluntary four-directional leaning task, the nMLBI group showed significantly smaller forward–backward stability range ($P=0.032$), right–left stability range ($P=0.019$), and stability area ($P=0.021$) than the HC group. Similarly, the MLBI group showed significantly smaller forward–backward stability range ($P=0.007$), right–left stability range ($P=0.006$), and stability area ($P=0.001$) than the HC group. However, there was no significant difference in these results between nMLBI and MLBI groups. Additionally, no significant difference was observed between the three groups for locus length, sway area, or locus length per unit area in each direction. Normalization by participant height did not influence the results for locus length or sway area.

DISCUSSION

In this study, according to the mean score of the Ten-Step Test, patients with PD were classified as nMLBI (score <1) or MLBI (score ≥ 1).^{17,18} To our knowledge, no other studies have compared PD patients and HCs based on the trunk movement trajectory amplitude and its CV during gait, nor have they categorized subgroups based on PD severity. In

addition, the postural control difference between PD patients and HCs in the mediolateral direction during weight-shifting tasks is controversial. Therefore, we aimed to address differences in mediolateral postural control among three groups (HCs, MLBI and nMLBI groups) during the weight-shifting task and gait. In patients with PD, both the right–left stability range and the forward–backward stability range were smaller than those in HCs during the weight-shifting task. The novel finding in this study was that patients in the MLBI group showed mediolateral postural sway and low variability during gait (Fig. 2).

In postural control examinations using a force plate, the movement of the COP was assessed and calculated as the stability area of the participants. In general, postural control is more stable with a wider stability area. Similarly, in the voluntary four-directional leaning test, postural control is more stable with a smaller sway area. Previous studies showed that the right–left stability range in PD patients equaled that in HCs in the voluntary four-directional leaning test, although the forward–backward stability range in PD patients was smaller than that in HCs.^{10–12} The present study showed that both the right–left stability range and the forward–backward stability range in the MLBI group were not different from those in the nMLBI group, although those parameters in both nMLBI and MLBI groups were smaller than those in HCs. These results suggest that PD patients may have postural control deficits in each of the four directions, not only in the forward–backward direction. The present study also suggests that for patients with PD, therapeutic

Table 3. Correlations between fall score (UPDRS item 13) and gait assessment parameters in PD patients

	P-value PD patients (n=40)
Gait velocity	0.53 (0.10)
Step stride	0.60 (-0.08)
Movement trajectory amplitude ML	0.022 (0.36)
CV of movement trajectory amplitude ML	0.57 (-0.09)
Movement trajectory amplitude VT	0.22 (-0.19)
CV of movement trajectory amplitude VT	0.59 (0.08)

Pearson's correlation coefficients shown in parentheses.

approaches may be necessary to widen the stability range not only in the forward–backward direction but also in the right–left direction.

In the gait analysis, ANCOVA was performed with HY stage as a covariate to compare the differences between MLBI and nMLBI groups. Other factors relating to disease severity (disease duration, LED and UPDRS part III) were comparable between nMLBI and MLBI groups. Therefore, gait analysis in the present study suggests that MLBI group is a subgroup with mediolateral balance impairments in patients with PD rather than a subgroup with classification determined by disease severity. The MLBI group showed a significant increase of ML movement trajectory amplitudes compared with the HC and nMLBI groups, whereas there was no significant difference in ML movement trajectory amplitudes between the HC and nMLBI groups. In addition, the MLBI group had a low variability in mediolateral trajectory amplitude compared with HCs and nMLBI group during gait. In patients with neurodegenerative diseases other than PD causing mediolateral balance impairments, both ML amplitudes and their CVs are higher than HCs during gait,^{22,26} which was not the case in the current study. The difference in the variability of ML amplitudes between PD and other neurodegenerative diseases during gait may be explained by bradykinesia in PD patients with basal ganglia disorders, in contrast to patients with other neurodegenerative diseases causing ataxia or disequilibrium.²⁷ The MLBI group also showed significantly slower gait velocities and shorter step strides than the nMLBI group, indicating that bradykinesia is more severe during gait in the MLBI group than in the nMLBI group. However, the MLBI group showed high ML amplitudes and low variability in the mediolateral direction during gait. Moreover, the sway area in the MLBI group during the voluntary left–right leaning test is comparable with those in HC and nMLBI groups by COP analysis (Table

4), indicating that the MLBI group may maintain postural control in the mediolateral direction to avoid exceeding their right–left stability ranges. Taken together, the low variability in ML amplitudes may be a compensatory strategy for PD patients to not widen their mediolateral postural sway during gait. It may be speculated that bradykinesia in PD patients provides postural control in the mediolateral direction with low variability of ML amplitudes during gait.

The fall score in the MLBI group was higher than that in the nMLBI group. In addition, the ML movement trajectory amplitude was significantly correlated with the fall score, whereas no other gait assessment parameters showed significant correlation with the fall score. Previous studies have shown that tandem gait may predict the risk of future falls in PD patients, although most falls in PD patients occur in the forward direction.^{8,9} Therefore, to avoid falls in MLBI patients, it is necessary to also focus on instabilities in the mediolateral direction and not only on those in the forward–backward direction, even though the ML amplitude variability during gait is normal-to-low in PD patients. PD patients have large mediolateral postural sway during external perturbation tasks with narrow stance width.²⁸ The current and previous studies suggest that physical therapists should advise PD patients to widen their step width during gait to decrease the fall risk. This is because wider step widths may compensate for instabilities in the mediolateral direction caused by large mediolateral postural sway.

This study has several limitations. First, PD patients were evaluated in the “on” state of their medication. Therefore, mediolateral postural sway in PD patients may not be applicable to PD patients in the “off” state. Second, questions remain concerning the association between mediolateral postural sway and disease severity because we did not test postural control in the mediolateral direction according to disease severity. Third, this was a cross-sectional study. Fu-

Table 4. COP analysis of each group

	HCs (n=20)	nMLBI (n=26)	MLBI (n=14)	P-value	P-value HCs vs nMLBI	P-value HCs vs MLBI	P-value nMLBI vs MLBI
Quiescent standing							
Locus length (cm)	85.9 (13.8)	89.6 (21.7)	97.8 (18.1)	0.19 ^a	0.77 ^b	0.17 ^b	0.39 ^b
Sway area (cm ²)	1.1 (0.5)	1.8 (1.1)	1.9 (1.1)	0.016 ^c	0.050 ^d	0.023 ^d	0.92 ^d
Locus length per unit area (cm/cm ²)	102.2 (68.7)	66.7 (38.8)	73.5 (58.7)	0.068 ^c	0.072 ^d	0.18 ^d	0.99 ^d
Voluntary forward leaning							
Locus length (cm)	36.2 (5.5)	36.1 (11.3)	36.9 (7.9)	0.95 ^a	0.99 ^b	0.97 ^b	0.95 ^b
Sway area (cm ²)	1.3 (0.6)	1.2 (0.8)	1.1 (0.5)	0.50 ^c	0.59 ^d	0.56 ^d	0.95 ^d
Locus length per unit area (cm/cm ²)	43.4 (37.9)	52.2 (58.1)	42.1 (20.5)	0.74 ^c	0.87 ^d	0.76 ^d	0.89 ^d
Voluntary backward leaning							
Locus length (cm)	38.1 (4.8)	37.6 (10.2)	39.3 (8.3)	0.54 ^c	0.56 ^d	0.95 ^d	0.71 ^d
Sway area (cm ²)	1.5 (0.9)	1.3 (0.8)	1.2 (0.5)	0.63 ^c	0.77 ^d	0.63 ^d	0.93 ^d
Locus length per unit area (cm/cm ²)	37.9 (22.4)	44.2 (45.6)	42.7 (23.3)	0.61 ^c	0.99 ^d	0.65 ^d	0.65 ^d
Voluntary right leaning							
Locus length (cm)	36.5 (5.8)	33.7 (9.0)	36.8 (8.1)	0.37 ^a	0.46 ^b	0.99 ^b	0.47 ^b
Sway area (cm ²)	1.6 (0.9)	1.2 (0.7)	1.3 (0.5)	0.38 ^c	0.35 ^d	0.89 ^d	0.75 ^d
Locus length per unit area (cm/cm ²)	31.3 (16.6)	49.0 (50.9)	32.8 (14.1)	0.67 ^c	0.66 ^d	0.84 ^d	0.97 ^d
Voluntary left leaning							
Locus length (cm)	36.6 (5.6)	33.2 (8.0)	37.1 (8.8)	0.19 ^a	0.30 ^b	0.97 ^b	0.27 ^b
Sway area (cm ²)	1.73 (1.0)	1.3 (0.8)	1.3 (0.4)	0.45 ^c	0.44 ^d	0.65 ^d	0.99 ^d
Locus length per unit area (cm/cm ²)	28.4 (13.5)	35.2 (20.8)	31.7 (12.0)	0.68 ^c	0.73 ^d	0.75 ^d	0.97 ^d
Forward–backward stability range (%)	38.5 (8.1)	31.4 (10.2)	31.0 (5.3)	0.006 ^a	0.032 ^b	0.007 ^b	0.98 ^b
Right–left stability range (%)	49.7 (5.2)	42.6 (11.2)	40.2 (9.1)	0.001 ^a	0.019 ^b	0.006 ^b	0.74 ^b
Stability area (%)	19.5 (5.8)	14.1 (7.1)	12.7 (4.3)	<0.001 ^a	0.021 ^b	0.001 ^b	0.71 ^b

Data presented as mean (SD).

^a One-way ANOVA; ^b Multiple comparison with Tukey's post-hoc test; ^c Kruskal–Wallis test; ^d Multiple comparison with Steel–Dwass post-hoc test.

ture studies should address whether postural control in the mediolateral direction is impaired as PD progresses.

CONCLUSION

This study suggests that PD patients with mediolateral balance impairments showed mediolateral postural sway during gait compared with those without mediolateral balance impairments. The low variability of mediolateral COM movements may compensate for instability caused by mediolateral postural sway during gait in PD patients with mediolateral balance impairments. However, the low

variability of mediolateral COM movements may lead to a narrow movement area and, thus, not contribute to preventing falls in PD patients. Taken together, in the rehabilitation approach for PD patients, it may be important to widen the stability area in the mediolateral direction and correct the stance width to decrease the fall risk.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

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