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ORIGINAL

Effects of Freezing of Gait on Spatiotemporal Variables, Ground Reaction Forces, and Joint Moments during Sit-to-walk Task in Parkinson's Disease

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Objective: This study aimed to analyze the effects of freezing of gait on spatiotemporal variables, ground reaction forces (GRFs), and joint moments during the sit-to-walk task at the preferred and maximum speeds in patients with Parkinson's disease (PD).

Method: The subjects were classified by a neurologist into 12 freezers, 12 non-freezers, and 12 controls. Sit-to-walk parameters were measured during three repetitions of the task in a random order at the preferred and maximum possible speeds.

Results: In the sit-to-walk task at the preferred speed, the freezers and non-freezers exhibited a higher peak anterior-posterior GRF (p<0.001) in the sit-to-stand phase and lower step velocity (p<0.001), step length (p<0.001), and peak anterior-posterior GRF (p<0.001) in the first-step phase than the controls. The freezers had higher peak anterior-posterior GRF (p<0.001) and peak moment of the hip joint (p=0.008) in the sit-to-stand phase than the non-freezers. In the sit-to-walk phase at the maximum speed, the freezers and non-freezers had lower peak moment of the hip joint (p=0.008) in the sit-to-stand phase than the controls. The freezers and non-freezers displayed lower step velocity (p<0.001) and peak anterior-posterior GRF (p<0.001) in the first-step phase than the controls. The freezers showed higher peak moments of the hip joint in the sit-to-stand phase than the non-freezers (p=0.008).

Conclusion: The PD patients had reduced control ability in sit-to-stand motions for efficient performance of the sit-to-walk task and reduced performance in the sit-to-walk task. Furthermore, the freezers displayed reduced control ability in the sit-to-stand task. Finally, the PD patients exhibited a lower ability to control dynamic stability with changes in speed than the controls.

Keywords: Parkinson's disease, Freezing of gait, Gait, GRF, Motor symptom

INTRODUCTION

Parkinson's disease (PD) is a neurodegenerative disease related to a progressive loss of dopaminergic neurons in the substantia nigra pars compacta in the basal ganglia (Carpinella et al., 2007). Its typical motor symptoms include tremor, rigidity, bradykinesia, postural instability, and freezing of gait (FOG), which manifest in the limbs of one side when the dopamine concentration within the striatum decreases to <60~70% (Niazmand et al., 2011). FOG affects approximately 50% of all PD patients (Peterson, Plotnik, Hausdorff & Earhart, 2012; Heremans et al., 2015) and usually occurs during turning, walking, passing through a narrow space, reaching the destination, and time-limited tasks (Heremans et al., 2015; Weiss et al., 2010). FOG leads to postural instability, which in turn causes secondary injuries such as those from a fall, thereby undermining quality of life, mobility, and independence (Moore, Peretz & Giladi, 2007; Spildooren et al., 2012).

Previous studies on FOG found that patients with FOG displayed lower gait coordination than those without FOG and the controls, and that FOG occurs more frequently during turning and backward walking than during forward walking (Peterson et al., 2012). FOG occurred in 88% and 100% of the patients in the FOG group during a task of passing through a narrow space and a rapid turning task, respectively (Snijders, Haaxma, Hagen, Munneke & Bloem, 2012). Furthermore, during treadmill walking, the FOG group showed shorter step lengths than the non-FOG group (Nanhoe-Mahabier et al., 2011). Therefore, PD patients with FOG are believed to have weaker gait ability than those without FOG. Gait ability has been reported to be reduced during rapid turning tasks or time-constrained tasks, but generalizable study findings are still lacking.

The sit-to-walk (STW) task involves a sequential postural transition from a sitting posture to standing and walking. Upon initiation of the motion, trunk flexion and hip and knee extension occur, and standing

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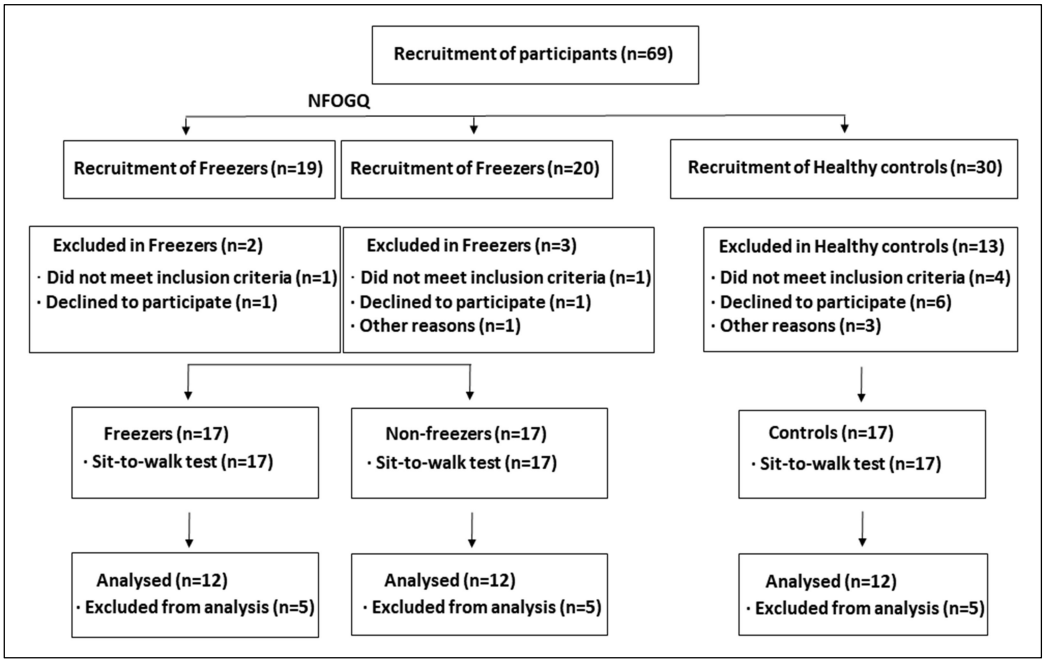

Figure 1. Flow diagram of participant selection

up from the chair and taking a step forward requires simultaneous forward and upward linear momentum (Buckley, Pitsikoulis & Hass, 2008; Van Uem et al., 2016). Approximately 80% of all PD patients have difficulty performing this task, which leads to postural imbalance and subsequent increases in the patient's risk of falling (Buckley et al., 2008, Van Uem et al., 2016). After analyzing performances in the sit-to-stand, gait initiation, and STW tasks in 12 PD patients, Buckley et al. (2008) reported that the patients showed a shorter step length and a slower step velocity. However, most studies that involved the STW task have been conducted on healthy elderly, with only a few studies on PD patients.

In essence, previous studies suggested that PD patients have much difficulty performing motions commonly performed in daily living, such as sitting, standing, sit-to-stand, and standing and walking, as well as STW, where these motions occur sequentially, and that FOG frequently occurs at initiation and termination, time-limited tasks, and turning and backward walking tasks (Peterson et al., 2012; Heremans et al., 2015). However, studies that investigate motion characteristics through changes in gait velocity during the STW task in PD patients are lacking. Hence, analysis of the features related to the dynamic stability of PD patients with FOG during the STW task based on preferred and maximum speeds would be meaningful.

Thus, this study aimed to analyze the changes in spatiotemporal variables, ground reaction forces (GRFs), and joint moments in relation to preferred and maximum speeds in PD patients with FOG, PD patients without FOG, and controls in the same age group.

METHODS

1. Participants

The study population was composed of patients diagnosed as having idiopathic PD by a neurology specialist on the basis of the UK Parkinson's Disease Society Brain Bank criteria (Hughes, Daniel & Lees, 2001). The inclusion criteria were individuals aged 50~75 years who can walk and move independently, with a modified Hoehn & Yahr (H&Y) stage 1~3 and Korean Mini Mental State Examination (K-MMSE) score of >24 and those who stably respond to antiparkinson medications. The exclusion criteria were patients with a history of cardiovascular, musculoskeletal, vestibular, or other neurological diseases; patients who required assistive devices for moving; and patients with a dyskinesia that is uncontrollable with drug therapy. The controls group included healthy older adults in a similar age group who had no history of illnesses related to cognitive impairment and gait disturbance in the past 6 months and no history of orthopedic surgery.

The PD group was divided into the freezers and non-freezers (12 subjects in each) based on the New Freezing of Gait Questionnaire (NFOGQ), and 12 participants were enrolled in the controls group. The flow diagram of the details of the study participation is shown in (Figure 1), and the physical characteristics of the participants are shown in (Table 1). All study-related procedures were approved by the institutional review board (IRB), and informed consents were obtained from the participants.

2. Measurements

This study was divided into two stages. In the first stage, the partici-

Table 1. Physical characteristics of all the participants

	Freezers (n=12)	Non-freezers (n=12)	Controls (n=12)	F-value	p-value
Age (years)	66.67±4.38	68.83±6.00	68.25±3.47	0.674	0.517
Height (cm)	158.83±9.08	157.73±7.22	160.30±9.29	0.270	0.765
Weight (kg)	57.88±8.97	61.07±8.43	61.53±9.54	0.584	0.563
BMI (kg/m^2)	22.86±2.24	24.55±3.13	23.84±2.20	1.319	0.281
K-MMSE (scores)	27.33±2.06	26.67±2.57	26.00±1.76	1.148	0.330

All data are presented as means ± standard deviations. BMI: body mass index, K-MMSE: Korean Mini Mental State Examination.

Table 2. Clinical characteristics of PD participants

	Freezers (n=12)	Non-freezers (n=12)	t-value	p-value
Disease duration (years)	9.83±4.26	5.96±1.83	2.890	0.008
Treatment duration (years)	8.95±4.35	3.52±2.26	3.836	0.001
UPDRS (scores)	60.47±9.59	38.13±5.90	6.800	0.000
UPDRSIII (scores)	33.38±6.16	27.96±4.38	2.450	0.023
H&Y (scores)	2.55±0.27	2.38±0.31	1.399	0.176
NFOGQ (scores)	19.18±5.62	–	–	–
L-Dopa equivalent dose (mg/day)	1,142.50±418.20	682.92±239.17	3.305	0.003

All data are presented as means ± standard deviations.

pants completed the informed consent form, Unified Parkinson Disease Rating Scale (UPDRS), modified H&Y test, NFOGQ test, and K-MMSE (Table 1, 2). In the second stage, the participants' physical characteristics were measured, and the participants warmed up for about 5 minutes. The participants were instructed to practice the STW task at their preferred and maximum speeds five times, and then the actual trials were begun. For the experiment, nine infrared cameras (Vicon MX-T10, Oxford Metrics, UK) and two GRF systems (OR6-7, AMTI, US) were used. All the measurements were taken at the "on" state (drugs were taken about 2~3 hours earlier), when the participants sufficiently felt the effects of the drugs (Willemssen, Müller, Schwarz, Hohnsbein & Falkenstein, 2008). The physical model was formulated using 39 round reflective markers according to the Plug in Gait Full Body Model (Vicon Motion Systems Ltd., Oxford, UK), a modified form of the Helen Hayes Marker Set.

3. Data processing

The STW task was performed at the participants' preferred and maximum speeds. The motion data and GRF data were collected and analyzed using the Nexus software (Vicon, UK). The measurements were taken three times, and the mean value was used for the analysis. The sampling frequency for the imaging and GRF data were 100 and 1,000 Hz, respectively. The collected data were filtered using a fourth-order Butterworth low-pass filter at 10 and 25 Hz, respectively (Jones, James, Thacker, Jones & Green, 2016). The events and phases were set as follows (Figure 2): Event 1 (E1) refers to the point at which the C7 marker moves forward (Seven, Akalan & Yucesoy, 2008); Event 2 (E2), the seat-off point at which the anterior-posterior GRF reaches the peak; Event 3 (E3), the heel-off point when the first step is taken (Buckley et al., 2008); Event 4 (E4), the heel strike point of the first step; and Event 5 (E5), the heel strike point of the second step. Phases were set to the intervals between each event. The variables for analysis were spatio-temporal variables (first and second step velocity, time, and length), anterior-posterior and vertical GRF, and peak hip, knee, and ankle joint moments in the sagittal plane.

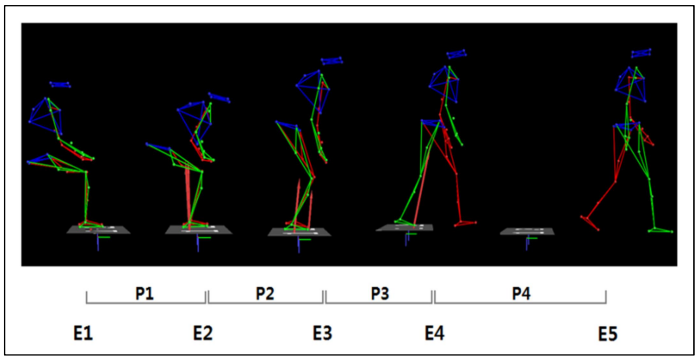

Figure 2. Definition of events and phases

Table 3. Spatiotemporal variables in P3

		Freezers	Non-freezers	Controls	*F*-value	Post hoc
Step velocity (m/s)	PS	1.12±0.25	1.14±0.37	1.91±0.78	11.981 (G)*	C>NF and F
	MS	1.40±0.46	1.44±0.22	2.42±0.90	24.903 (S)*	C>NF and F
	Z-value	2.750*	2.513*	2.490*	1.077 (G×S)	
Step time (s)	PS	0.35±0.07	0.37±0.05	0.38±0.02	0.430 (G)	–
	MS	0.34±0.05	0.33±0.04	0.34±0.02	24.722 (S)*	–
	Z-value	1.072	2.404*	2.755*	1.718 (G×S)	
Step length (m)	PS	0.39±0.10	0.41±0.13	0.70±0.26	16.103 (G)*	C>NF and F
	MS	0.46±0.12	0.48±0.09	0.82±0.28	10.857 (S)*	C>NF and F
	Z-value	2.347*	1.766	1.609	0.432 (G×S)	

All data are presented as means ± standard deviations. *F*-value: Two-way ANOVA with repeated measures, *Z*-value: Wilcoxon signed-rank test between the two speeds, G: main effects between the groups, S: main effects within speeds, G×S: interaction effects between the groups and speed, PS: preferred speed, MS: maximum speed; *$p<0.05$.

Table 4. Spatiotemporal variables in P4

		Freezers	Non-freezers	Controls	*F*-value	Post hoc
Step velocity (m/s)	PS	0.78±0.17	0.78±0.19	0.85±0.33	2.843 (G)	–
	MS	0.97±0.21	1.04±0.23	1.33±0.44	40.075 (S)*	C>F
	Z-value	2.629*	2.845*	2.824*	3.376 (G×S)*	
Step time (s)	PS	0.57±0.07	0.58±0.04	0.54±0.06	3.930 (G)*	–
	MS	0.52±0.06	0.50±0.05	0.45±0.04	89.720 (S)*	F and NF>C
	Z-value	2.940*	2.827*	2.950*	1.375 (G×S)	
Step length (m)	PS	0.44±0.07	0.45±0.09	0.45±0.17	0.840 (G)	–
	MS	0.49±0.07	0.52±0.09	0.59±0.17	17.634 (S)*	–
	Z-value	2.048*	2.592*	2.091*	1.691 (G×S)	

All data are presented as means ± standard deviation. *F*-value: Two-way ANOVA with repeated measures, *Z*-value: Wilcoxon signed-rank test between the speeds, G: main effects between the groups, S: main effects within the speeds, G×S: interaction effects between the groups and speeds, PS: preferred speed, MS: maximum speed; *$p<0.05$.

4. Statistical analyses

Statistical analyses were performed using the SPSS 22.0 software. The Shapiro-Wilk test revealed that the data followed a significantly non-normal distribution. Therefore, the interaction and main effects of the groups (freezers, non-freezers, and controls) and speed (preferred and maximum speeds) during STW task were analyzed with two-way repeated-measures analysis of variance (ANOVA), and intergroup differences were analyzed with the Kruskal-Wallis *H* test. The Mann-Whitney *U* test was used as the post hoc analysis, and differences in speed were analyzed with the Wilcoxon signed-rank test. Statistical significance was set at 0.05.

RESULTS

1. Spatiotemporal variables

In P3 (Table 3), step velocity was significantly lower in the freezers and non-freezers than in the controls group at both the preferred and maximum speeds. Post hoc analysis revealed that step velocity was significantly higher at maximum speed than at the preferred speed in the freezers ($p=0.006$), non-freezers ($p=0.012$), and controls ($p=0.013$). Step time was significantly shorter at maximum speed than at the preferred speed in the non-freezers ($p=0.016$) and controls ($p=0.006$). Step length was significantly shorter at both the preferred and maximum speeds in the non-freezers and freezers as compared with the controls. Post hoc analysis revealed that freezers ($p=0.019$) had a significantly longer step length at the maximum speed than at the preferred speed.

In P4 (Table 4), post hoc analysis revealed that step velocity was significantly higher at the maximum speed than at the preferred speed in the freezers (p=0.009), non-freezers (p=0.004), and controls (p=0.005). Furthermore, step time was significantly longer at the maximum speed in the freezers and non-freezers than in the controls. Post hoc analysis revealed that freezers (p=0.003), non-freezers (p=0.005), and controls (p=0.003) had significantly shorter step time at the maximum speed than at the preferred speed. Furthermore, post hoc analysis revealed that step length was significantly longer at the maximum speed than at the preferred speed in the freezers (p=0.041), non-freezers (p=0.010), and controls (p=0.037).

2. Peak GRFs

Results for the left GRFs in the phase between E1 and E3 (standing from a sitting posture) are shown in (Table 5). The freezers and non-freezers had significantly greater anterior-posterior GRF than the controls at the preferred speed. At the maximum speed, the freezers had significantly greater anterior-posterior GRF than the non-freezers and controls. In terms of peak vertical GRF, the non-freezers had significantly greater peak vertical GRF at the maximum speed than at the preferred speed (p=0.023).

Results for the right GRFs in the E1-E3 phase are shown in (Table 6). The freezers had significantly greater anterior-posterior GRF than the controls and non-freezers at the preferred speed, and the freezers had significantly greater anterior-posterior GRF than the controls at the maximum speed. Furthermore, the non-freezers (p=0.003) and controls (p=0.012) had significantly greater anterior-posterior GRF at the maximum speed than at the preferred speed.

In terms of GRF at P3 (Table 7), the freezers and non-freezers had significantly smaller peak anterior-posterior GRF than the controls at both the preferred and maximum speeds. In the post hoc analysis for speed, the freezers (p=0.003), non-freezers (p=0.002), and controls (p=0.003) all showed significantly greater peak anterior-posterior GRF at the maximum speed than at the preferred speed. In addition, the freezers had significantly smaller peak vertical GRF than the non-freezers at the preferred speed, and the non-freezers had significantly smaller vertical GRF than the controls at the maximum speed.

3. Peak joint moments

The peak flexion/extension moment for the first step occurred from E1 to E3 (Table 8). Post hoc analysis revealed that the peak hip flexion moment was significantly greater at the maximum speed than at the preferred speed in the non-freezers (p=0.036) and controls (p=0.011). The peak knee flexion moment was significantly greater at the maximum

Table 5. Peak anterior-posterior and vertical GRFL for P1 and P2 (Unit: N/BW)

		Freezers	Non-freezers	Controls	F-value	Post hoc
Peak Anterior-posterior	PS	0.54±0.14	0.27±0.13	0.27±0.11	14.958 (G)*	F>NF and C
	MS	0.60±0.19	0.35±0.15	0.37±0.15	19.260 (S)*	F>C and NF
	Z-value	2.119*	1.786	2.449*	0.488 (G×S)	
Peak vertical	PS	6.10±0.91	6.17±0.84	6.62±0.61	1.652 (G)	–
	MS	6.21±0.69	6.50±1.00	6.81±0.73	6.417 (S)*	–
	Z-value	0.941	2.276*	1.956	0.631 (G×S)	

All data are presented as means ± standard deviations. F-value: Two-way ANOVA with repeated measures, Z-value: Wilcoxon signed-rank test between the two speeds, G: main effects between the groups, S: main effects within the speeds, G×S: interaction effects between the groups and speeds, PS: preferred speed, MS: maximum speed; GRFL: ground reaction force on the left; *p<0.05.

Table 6. Peak anterior-posterior and vertical GRFR for P1 and P2 (Unit: N/BW)

		Freezers	Non-freezers	Controls	F-value	Post hoc
Peak Anterior-posterior	PS	0.79±0.19	0.44±0.15	0.48±0.13	5.079 (G)*	F>C and NF
	MS	0.84±0.20	0.72±0.47	0.65±0.18	16.685 (S)*	F>C
	Z-value	1.419	2.937*	2.512*	2.588 (G×S)	
Peak vertical	PS	7.11±0.94	6.63±0.76	6.58±0.68	0.939 (G)	–
	MS	6.82±0.49	6.53±1.20	6.78±0.48	0.303 (S)	–
	Z-value	1.569	0.941	1.334	1.486 (G×S)	

All data are presented as means ± standard deviations. F-value: Two-way ANOVA with repeated measures, Z-value: Wilcoxon signed-rank test between the speeds, G: main effects between the groups, S: main effects within the speeds, G×S: interaction effects between the groups and speeds, PS: preferred speed, MS: maximum speed, GRFR: ground reaction force on the right; *p<0.05.

Table 7. Peak anterior-posterior and vertical GRF for P3 (Unit: N/BW)

		Freezers	Non-freezers	Controls	*F*-value	Post hoc
Peak Anterior-posterior	PS	1.15±0.30	1.24±0.30	1.67±0.33	13.700 (G)*	C>NF and F
	MS	1.49±0.36	1.71±0.35	2.12±0.25	74.628 (S)*	C>NF and F
	Z-value	2.982*	3.059*	2.982*	0.750 (G×S)	
Peak vertical	PS	9.49±0.41	9.68±0.29	10.06±0.55	6.270 (G)*	NF>F
	MS	9.79±0.37	9.41±0.86	10.23±0.58	0.403 (S)	C>NF
	Z-value	1.804	1.177	0.622	2.765 (G×S)	

All data are presented as means ± standard deviations. *F*-value: Two-way ANOVA with repeated measures, *Z*-value: Wilcoxon signed-rank test between the speeds, G: main effects between the groups, S: main effects within the speeds, G×S: interaction effects between the groups and speeds, PS: preferred speed, MS: maximum speed, GRF: ground reaction force; *$p<0.05$.

Table 8. Peak flexion/extension joint moments of the lower extremities for the first step during E1-E3 (Unit: N · m/BM)

		Freezers	Non-freezers	Controls	*F*-value	Post hoc
Hip	PS	0.91±0.17	0.74±0.26	0.85±0.19	1.543 (G)	-
	MS	0.92±0.13	0.82±0.30	0.96±0.21	8.957 (S)*	-
	Z-value	0.196	2.091*	2.550*	2.355 (G×S)	
Knee	PS	0.84±0.20	0.79±0.17	0.79±0.20	0.400 (G)	-
	MS	0.89±0.19	0.84±0.19	0.81±0.22	7.857 (S)*	-
	Z-value	2.358*	1.609	1.115	0.703 (G×S)	

All data are presented as means ± standard deviations. *F*-value: Two-way ANOVA with repeated measures, *Z*-value: Wilcoxon signed-rank test between the speeds, G: main effects between the groups, S: main effects within the speeds, G×S: interaction effects between the groups and speeds, PS: preferred speed, MS: maximum speed; *$p<0.05$.

Table 9. Peak dorsiflexion/plantarflexion joint moment of the ankle for the first step during E3-E5 (Unit: N · m/BM)

		Freezers	Non-freezers	Controls	*F*-value	Post hoc
Ankle	PS	0.30±0.19	0.28±0.07	0.31±0.14	0.470 (G)	-
	MS	0.36±0.16	0.34±0.12	0.43±0.18	28.447 (S)*	-
	Z-value	1.430	2.752*	2.984*	1.778 (G×S)	

All data are presented as means ± standard deviations. *F*-value: Two-way ANOVA with repeated measures, *Z*-value: Wilcoxon signed-rank test between the speeds, G: main effects between the groups, S: main effects within the speeds, G×S: interaction effects between the groups and speeds, PS: preferred speed, MS: maximum speed; *$p<0.05$.

speed than at the preferred speed in the freezers ($p=0.018$). Peak ankle dorsiflexion/plantarflexion moment occurred from E3 to E5 (between the first and second steps; Table 9). Post hoc analysis revealed that peak ankle dorsiflexion moment was significantly greater at the maximum speed than at the preferred speed in the non-freezers ($p=0.006$) and controls ($p=0.003$).

The peak flexion/extension moments for the second step occurred from E1 to E3 (Table 10). The peak hip flexion moment was significantly greater in the freezers than in the non-freezers at the preferred speed and significantly smaller in the non-freezers than in the freezers and controls at the maximum speed. Post hoc analysis revealed that the controls ($p=0.007$) had significantly greater peak hip flexion moment at the maximum speed than at the preferred speed. The peak knee flexion moment was significantly greater at the maximum speed than at the preferred speed in the freezers ($p=0.020$). The peak ankle dorsiflexion/plantarflexion moment occurred from E3 to E5 (between the first and second steps; Table 11). The peak ankle dorsiflexion moment was significantly smaller in the non-freezers than in the controls at both the preferred and maximum speeds.

Table 10. Peak flexion/extension joint moments of the lower extremities for the second step during E1-E3 (Unit: N · m/BM)

		Freezers	Non-freezers	Controls	*F*-value	Post hoc
Hip	PS	0.89±0.15	0.67±0.15	0.83±0.21	5.668 (G)*	F>NF
	MS	0.95±0.20	0.71±0.28	0.99±0.21	9.945 (S)*	C and F>NF
	Z-value	0.944	0.354	2.714*	1.865 (G×S)	
Knee	PS	0.83±0.18	0.74±0.14	0.73±0.17	1.443 (G)	–
	MS	0.86±0.16	0.78±0.16	0.75±0.18	6.708 (S)*	–
	Z-value	2.320*	1.179	1.203	0.143 (G×S)	

All data are presented as means ± standard deviations. *F*-value: Two-way ANOVA with repeated measures, *Z*-value: Wilcoxon signed-rank test between the speeds, G: main effects between the groups, S: main effects within the speeds, G×S: interaction effects between the groups and speeds, PS: preferred speed, MS: maximum speed; *$p<0.05$.

Table 11. Peak dorsiflexion/plantarflexion joint moment of the ankle for the second step during E3-E5 (Unit: N · m/BM)

		Freezers	Non-freezers	Controls	*F*-value	Post hoc
Ankle	PS	0.84±0.32	0.88±0.19	1.15±0.17	5.349 (G)*	C>NF
	MS	0.92±0.39	0.93±0.27	1.21±0.19	3.141 (S)	C>NF
	Z-value	1.100	1.295	2.090*	0.091 (G×S)	

All data are presented as means ± standard deviations. *F*-value: Two-way ANOVA with repeated measures, *Z*-value: Wilcoxon signed-rank test between the speeds, G: main effects between the groups, S: main effects within the speeds, G×S: interaction effects between the groups and speeds, PS: preferred speed, MS: maximum speed; *$p<0.05$.

DISCUSSION

The purpose of this study was to analyze the spatiotemporal variables, GRF, and joint moments during the STW task in relation to preferred and maximum speeds in PD patients with FOG, PD patients without FOG, and healthy controls. Our findings show that the PD group had significantly lower first-step velocity and length, as well as peak anteroposterior GRF, which affects both, during the STW task at the preferred speed than the healthy controls. This suggests that the PD patients had increased difficulty with the STW task at their preferred speed. Furthermore, the PD patients showed significantly lower first-step velocity, and length and anteroposterior GRF during the STW task at the maximum speed (Buckley et al., 2008; Mak, Levin, Mizrahi & Hui-Chan, 2003).

In an analysis of STW task in PD patients and controls in the same age group, Buckley et al. (2008) reported that the PD group took a longer time to complete the task, reached a similar height as the peak height of the center of mass, and had slower vertical center of mass velocity, shorter step length, and slower step velocity. On the basis of these findings, the study suggested that PD patients not only had decreased ability to stand from a sitting posture and initiate gait but also had decreased ability to appropriately combine both tasks, which led to lower fluidity and efficiency of the STW task. Mak et al. (2003) analyzed the sit-to-stand phase in PD patients and healthy controls and reported that the PD patients showed more difficulty performing the sit-to-stand motion, with smaller anteroposterior and vertical GRF and peak hip joint moment. Furthermore, the PD group had smaller hip joint moment than the controls. These results were suggested to be due to a lack or imbalance of mobilized motor unit activities, insufficiency of muscle strength produced by the hip flexors (Frank, Horak & Nutt, 2000; Teasdale, Phillips & Stelmach, 1990), and elevated concurrent antagonist contraction (Beckley, Bloem, Van Dijk, Roos & Remler, 1991; Horak, Nutt & Nashner, 1992). Inkster et al. (2003) analyzed the sit-to-stand task in relation to drug therapy in PD patients (n=10) and healthy controls (n=10) in a similar age group and found that the PD patients not receiving drug therapy had smaller peak hip and knee joint moments than the controls, which led to lower ability to perform the sit-to-stand task. They suggested that these results are attributable to the weakening of muscles that affect sit-to-stand performance, which is in turn due to postural instability and deteriorated coordination to generate proper momentum. Similar to these previous findings, we found that the PD group had significantly lower first-step velocity and length and peak anteroposterior GRF, which affects both, in the E1-E3 phase, where patients stand from a sitting posture, during the STW task at the preferred speed.

In our study, the freezers had greater peak anteroposterior GRF and peak flexion moments than the non-freezers in the E1-E3 phase during the STW task at the preferred speed and greater peak hip flexion moment than the non-freezers at the maximum speed. Furthermore, the freezers showed smaller peak vertical GRF in the second step than the non-freezers, which suggests that they had significantly decreased ability to generate momentum to transition to walking in the sit-to-stand task. The reduced ability to generate and controls force, and

generate momentum to walk elevate the risk of falling, thereby undermining patients' activities of daily living and quality of life. Inkster and Eng (2004) reported that PD patients showed an exaggerated movement using the hip flexion strategy when initiating the sit-to-stand motion, based on which the authors suggested that PD patients usually use the hip strategy to ensure postural stability during sit-to-stand. Moreover, De Souza, Curtarelli Mde, Mukherjee and Dionisio (2011) reported that PD patients showed greater peak hip flexion moment than controls. Our findings between freezers and non-freezers were similar to the findings of Inkster and Eng (2004) and De Souza et al. (2011).

Brown et al. (2015) analyzed gait tasks in 22 healthy elderly and reported that step length increased and step time decreased with increasing gait velocity. Frenkel-Toledo et al. (2005) found that PD patients showed reduced stride length, increased stride time, and decreased gait velocity at a speed below the preferred speed, but they showed increased stride length, decreased stride time, and increased gait velocity at a speed above the preferred speed. Overall, healthy elderly (Brown et al., 2015) and PD patients (Frenkel-Toledo et al., 2005) seem to appropriately adapt to changes in velocity, which is in conflict with our findings.

In the present study, the controls seemed to controls speed change by increasing the peak anterior-posterior GRF and peak hip flexion moment from E1 to E3 and increasing peak ankle dorsiflexion moment in P3. However, the freezers and non-freezers did not demonstrate significant elevation of the peak hip flexion moment in E1-E3 and peak ankle dorsiflexion moment in P3. The freezers did not show significant differences in peak anteroposterior GRF and peak hip flexion moment in E1-E3 and peak ankle dorsiflexion moment in P3. These results were contrary to the findings of Frenkel-Toledo et al. (2005). Our findings suggest that the freezers and non-freezers had reduced ability to adapt to speed change as compared with the controls during the STW task and that this is more evident in the freezers.

CONCLUSION

This study aimed to investigate the spatiotemporal variables, GRFs, and joint moments during the STW task in relation to preferred and maximum speeds in PD patients with FOG, PD patients without FOG, and healthy controls in the same age group. The following conclusions were drawn: The PD patients showed a decreased ability to control the sit-to-stand motion to efficiently perform the STW task and decreased ability to perform the STW task. Furthermore, the freezers showed a decreased ability to controls the sit-to-stand motion and ability to generate momentum to transition from sit-to-stand to walking. Finally, the PD patients had lower ability to control dynamic stability when changing speed than the controls. Therefore, the STW task seems to be an effective tool to measure movement characteristics in healthy elderly and PD patients and to detect FOG in PD patients.

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