Comprehensive Analysis of Walking Characteristics of Patients with Parkinson's disease: Impact of Freezing of Gait

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Abstract

Patients with Parkinson's disease (PD) suffer from walking disturbances. This study was done to comprehensively analyze walking characteristics of PD, including forward and backward walking and turning. Impacts of freezing of gait (FoG) were also determined. Forward and backward walking and 360° turning was recorded at preferred speed in defined 'off' state. PD showed narrower step length, slower walking speed, and higher asymmetry index (AI) of step length during forward and backward walking. During turning, PD had more turning steps, longer turning time, and shorter step length than control. There was no difference at forward walking according to FoG, but freezer showed narrower step length and decreased range of motion in ankle joints at backward walking. Freezer showed longer step time and higher AI of step length at turning. The severity of FoG was correlated with step length and walking speed during forward and backward walking, total step count, total step time, and walking speed during turning. Comprehensive analysis showed that PD had narrower step length, slower walking speed, and increased asymmetry of step length. These features were the most prominent during turning, followed by backward and forward walking. Impacts of FoG were also the most prominent during turning.

Introduction

Patients with Parkinson's disease (PD) experience considerable difficulty in locomotion such as walking, turning, complex motor tasks, and cognitive tasks.[1,2] Walking disturbances can result in recurrent falls and fall-related injuries that can lead to loss of independence.[3,4] Mobility assessment of PD patients has been conducted using various tasks such as forward and backward walking, sit-to-walk, and turning.[5–8] Forward walking is a basic task of human locomotion. It has been the most commonly investigated by previous studies. Backward walking, a complex task that inevitably occurs in activities of daily living, involves turning, sitting back, and moving backward. It frequently leads the elderly to fall.[9–11] Turning includes 20% of all steps in daily activities. It is a challenging component of locomotor ability due to the need of complex integration between functionally different control mechanisms.[7,12] Freezing of gait (FoG) is defined as a sudden stopping or decreased stepping despite the intention to continue walking. It frequently occurs in PD patients, with an estimated prevalence of 30∼60%.[13,14] It is related to postural instability and balance impairment, and a major risk factor for falling.[15,16]

Studies on walking of PD patients have revealed that PD patients show short step and stride length, slow walking speed, high gait variability, and small range of motion (RoM) of lower limb joints during forward walking.[17–19] In backward walking, PD patients often lose their balance and fall as a result of backward moving.[20,21] Studies on turning of PD patients have revealed that they show slow walking speed and short step length.[7,22] PD patients also show an 'en-bloc' turn due to axial rigidity and loss of axial flexibility.[6,7] Turning difficulty is particularly implicated in patients with FoG who show a high incidence of fall.[22] PD patients with FoG show slower walking speed and shorter step and stride length than those without FoG.[23–25] However, thorough studies that analyze forward and backward walking of PD patients are still lacking. And, only a few studies have been conducted on the kinematics of backward gait in PD

patients. Also, few studies have analyzed turning task in patients with FoG. Studies have shown varied and conflicted results regarding walking characteristics of PD patients due to differences in the experimental condition and on-off status of drug during tests. There is a need to analyze walking characteristics of PD patients comprehensively, including forward and backward walking and turning concurrently. Thus, the objective of this study was to analyze walking characteristics of PD patients with and without FoG comprehensively, focusing on spatio-temporal and kinematic characteristics of forward and backward walking and turning using three-dimensional motion analysis system.

Results

1. Forward and backward walking

1.1 Participant characteristics

There was no difference in general characteristics between PD patients and control subjects (Supplementary table S1). Subjects in the freezer group were taller than those in the non-freezer group. They also showed longer symptom duration, longer treatment duration, higher Mini-mental status examination (MMSE) score, higher levodopa-equivalent dosage (LED), and higher Hoehn and Yahr (HY) stage than those in the non-freezer group.

1.2 Characteristics of forward walking

PD patients showed shorter step length and normalized step length (the step length divided by the height of each participant), slower walking speed, higher asymmetry index (AI) of step length, and lower toe clearance height than controls for both steps (Table 1). Although there was no significant difference in walking characteristics between freezer and non-freezer groups, the freezer group showed more difference than the non-freezer group compared to the control group. The PD group, especially the non-freezer group, showed difference in cadence and step time between steps.

Table 1
Characteristics of forward walking

	Step	PD patients	Freezer (F)	Non-freezer (NF)	Control (C)	post-hoc
Cadence (step/min)	MAS	117.87 ± 11.98[#]	115.03 ± 13.02	120.14 ± 10.73[#]	115.65 ± 10.07	ns
	LAS	115.65 ± 10.07[#]	113.66 ± 13.69	116.92 ± 11.36[#]	116.66 ± 7.92	ns
Step time (s)	MAS	0.52 ± 0.05[#]	0.53 ± 0.06	0.50 ± 0.04[#]	0.52 ± 0.05	ns
	LAS	0.53 ± 0.06[#]	0.54 ± 0.06	0.52 ± 0.05[#]	0.52 ± 0.04	ns
Step length (m)	MAS[¶,*]	0.50 ± 0.10	0.47 ± 0.11	0.52 ± 0.08	0.60 ± 0.08	C > NF,F
	LAS[¶,*]	0.51 ± 0.10	0.48 ± 0.11	0.53 ± 0.08	0.60 ± 0.08	C > F
Normalized step length (m)	MAS[¶,*]	0.32 ± 0.06	0.30 ± 0.07	0.34 ± 0.05	0.38 ± 0.05	C > NF,F
	LAS[¶,*]	0.32 ± 0.06	0.30 ± 0.06	0.34 ± 0.05	0.38 ± 0.05	C > NF,F
Walking speed (m/s)	MAS[¶,*]	0.98 ± 0.25	0.91 ± 0.27	1.04 ± 0.21	1.13 ± 0.21	C > F
	LAS[¶,*]	0.98 ± 0.25	0.91 ± 0.28	1.03 ± 0.21	1.13 ± 0.21	C > F
AI of step time (%)		6.38 ± 3.44	6.57 ± 3.41	6.24 ± 3.51	4.60 ± 2.64	ns
AI of step length (%)[*,¶]		7.61 ± 5.00	9.02 ± 6.14	6.48 ± 3.58	4.74 ± 3.11	F > C
Toe clearance height (cm)	MAS[¶,*]	8.24 ± 1.43	7.95 ± 1.40	8.48 ± 1.43	9.95 ± 1.23	C > NF,F
	LAS[¶,*]	8.40 ± 1.38	7.99 ± 1.26	8.74 ± 1.40	10.01 ± 1.14	C > NF,F
ROM of hip joint (°)	MAS*	41.49 ± 7.79	39.44 ± 6.40	43.14 ± 8.49	45.73 ± 6.00	C > F
	LAS	42.01 ± 7.87	39.86 ± 5.84	43.74 ± 8.89	45.58 ± 7.37	ns
ROM of knee joint (°)	MAS	56.66 ± 9.08	55.92 ± 6.75	57.25 ± 10.65	59.29 ± 6.59	ns
	LAS	57.05 ± 8.22	56.20 ± 7.15	57.73 ± 9.04	61.27 ± 6.43	ns

	Step	PD patients	Freezer (F)	Non-freezer (NF)	Control (C)	post-hoc
ROM of ankle joint (°)	MAS	30.68 ± 10.77	27.65 ± 5.70	33.12 ± 13.12	30.14 ± 5.45	ns
	LAS	30.67 ± 11.46	29.65 ± 12.12	31.49 ± 11.01	31.17 ± 7.15	ns
Maximum anti-phase (°)		12.05 ± 4.28	11.35 ± 4.21	12.61 ± 4.32	13.81 ± 3.97	ns

All data are given as mean ± standard deviations. MAS: more affected side; LAS: less affected side; AI: asymmetry index; ROM: range of motion; ¶: Denotes significant difference between PD and control ($p < 0.05$); *: Denotes significant difference between freezer; non-freezer; and control ($p < 0.05$); #: Denotes significant difference between step ($p < 0.05$).

1.3 Characteristics of backward walking

During backward walking, differences between PD and control group showed the same pattern as differences in spatio-temporal characteristics during forward walking (shorter the step length and normalized step length, slower walking speed, and higher AI of step length for both steps) (Table 2). However, kinematic characteristics of backward walking showed much more differences between PD and control groups than those of forward walking (toe clearance height, range of motion (RoM) of all lower limb joints). Backward walking also showed differences in step length and RoM of ankle joints for more-affected side (MAS) step between freezer and non-freezer groups. The non-freezer group showed difference in cadence, step time, toe clearance height, and RoM of ankle joints between steps.

Table 2
Characteristics of backward walking

	Step	PD patients	Freezer (F)	Non-freezer (NF)	Control (C)	post-hoc
Cadence (step/min)	MAS	118.23 ± 17.90	119.78 ± 18.65	116.99 ± 17.45[#]	110.76 ± 14.62	ns
	LAS	116.23 ± 17.03	118.84 ± 19.19	114.13 ± 15.05[#]	111.01 ± 18.37	ns
Step time (s)	MAS	0.52 ± 0.08	0.52 ± 0.09	0.52 ± 0.07[#]	0.55 ± 0.08	ns
	LAS	0.53 ± 0.07	0.51 ± 0.08	0.54 ± 0.07[#]	0.56 ± 0.09	ns
Step length (m)	MAS[¶,*]	0.28 ± 0.10	0.25 ± 0.11	0.30 ± 0.07	0.41 ± 0.07	C > NF > F
	LAS[¶,*]	0.28 ± 0.09	0.26 ± 0.09	0.30 ± 0.09	0.42 ± 0.07	C > NF,F
Normalized step length (m)	MAS[¶,*]	0.18 ± 0.06	0.15 ± 0.07	0.20 ± 0.04	0.25 ± 0.05	C > NF > F
	LAS[¶,*]	0.18 ± 0.06	0.16 ± 0.05	0.19 ± 0.05	0.26 ± 0.04	C > NF,F
Walking speed (m/s)	MAS[¶,*]	0.50 ± 0.18	0.44 ± 0.18	0.55 ± 0.17	0.71 ± 0.20	C > F
	LAS[¶,*]	0.50 ± 0.18	0.44 ± 0.18	0.55 ± 0.17	0.71 ± 0.20	C > F
AI of step time (%)		7.97 ± 4.09	8.47 ± 4.37	7.58 ± 3.87	6.71 ± 4.83	ns
AI of step length (%)[*,¶]		16.43 ± 11.17	18.52 ± 12.70	14.76 ± 9.64	7.84 ± 3.90	F > C
Toe clearance height (cm)	MAS[¶,*]	6.13 ± 1.08	5.84 ± 1.23	6.20 ± 0.95[#]	8.93 ± 2.95	C > NF,F
	LAS[¶,*]	6.21 ± 1.20	6.12 ± 1.39	6.29 ± 1.04[#]	8.70 ± 2.38	C > NF,F
ROM of hip joint (°)	MAS[¶,*]	29.04 ± 9.53	27.67 ± 9.17	30.14 ± 9.80	38.86 ± 7.40	C > NF,F
	LAS[¶,*]	30.01 ± 9.27	27.61 ± 8.89	31.93 ± 9.24	38.71 ± 8.02	C > F
ROM of knee joint (°)	MAS[¶,*]	34.42 ± 11.58[#]	33.28 ± 10.70	35.33 ± 12.32	48.50 ± 14.09	C > NF,F
	LAS[¶,*]	36.87 ± 10.83[#]	34.87 ± 10.87	38.47 ± 10.68	52.08 ± 12.61	C > NF,F

	Step	PD patients	Freezer (F)	Non-freezer (NF)	Control (C)	post-hoc
ROM of ankle joint (°)	MAS[¶,*]	25.20 ± 7.68	21.70 ± 6.60[#]	28.00 ± 7.40[#]	30.84 ± 8.70	C > NF > F
	LAS[¶,*]	25.38 ± 8.16	22.43 ± 6.05[#]	27.74 ± 8.91[#]	31.99 ± 11.02	C > F
Maximum anti-phase (°)		7.03 ± 2.91	7.15 ± 3.38	6.94 ± 2.52	8.35 ± 3.47	ns

All data are given as mean ± standard deviations. MAS: more affected side; LAS: less affected side; AI: asymmetry index; ROM: range of motion; [¶]: Denotes significant difference between PD and control ($p < 0.05$); *: Denotes significant difference between freezer; non-freezer; and control ($p < 0.05$); [#]: Denotes significant difference between step ($p < 0.05$).

2. 360° turning

2.1 Participant characteristics

There was no significant difference in general characteristics between PD patients and control subjects (Supplementary table S2). Subjects in the freezer group showed longer symptom duration, longer treatment duration, higher MMSE score, and higher LED than those in the non-freezer group.

2.2 Characteristics of 360°turning

During 360^{o} turning, differences in walking characteristics between PD and control groups showed the same pattern as differences in spatio-temporal characteristics of forward and backward walking (shorter the step length, slower walking speed, and higher AI of step length for both direction) (Table 3). Kinematic characteristics of turning showed differences between PD and control groups for both direction except for RoM of ankle joint. The freezer group showed higher AI of step length than the non-freezer group for both directions. The control group showed differences in step length, walking speed, and AI of step length according to turning direction.

Table 3

Characteristics of 360° turning

	Direction	PD patients	Freezer (F)	Non-freezer (NF)	Control (C)	post-hoc
Cadence (step/min)	MAS	127.80 ± 14.61	129.81 ± 14.67	126.22 ± 14.59	129.80 ± 6.92	ns
	LAS	128.02 ± 15.23	130.86 ± 14.83	125.81 ± 15.40	128.60 ± 8.76	ns
Step time (s)	MAS	0.48 ± 0.06	0.47 ± 0.05	0.49 ± 0.06	0.47 ± 0.03	ns
	LAS	0.48 ± 0.06	0.47 ± 0.05	0.49 ± 0.06	0.47 ± 0.03	ns
Step length (m)	MAS¶,*	0.32 ± 0.07	0.30 ± 0.08	0.33 ± 0.06	0.43 ± 0.09#	C > NF,F
	LAS¶,*	0.32 ± 0.08	0.30 ± 0.09	0.34 ± 0.08	0.41 ± 0.07#	C > NF,F
Walking speed (m/s)	MAS¶,*	0.67 ± 0.15	0.63 ± 0.15	0.70 ± 0.15	0.93 ± 0.20#	C > NF,F
	LAS¶,*	0.68 ± 0.19	0.65 ± 0.20	0.71 ± 0.18	0.88 ± 0.15#	C > NF,F
AI of step time (%)	MAS	14.30 ± 3.67	14.63 ± 4.69	14.04 ± 2.68	12.24 ± 5.28	ns
	LAS	14.32 ± 3.72	14.67 ± 4.17	14.04 ± 3.38	13.49 ± 5.29	ns
AI of step length (%)	MAS¶,*	25.63 ± 8.37	28.40 ± 9.02	23.46 ± 7.25	14.39 ± 2.74#	F > NF > C
	LAS¶,*	26.51 ± 10.15	29.24 ± 11.82	24.39 ± 8.20	12.23 ± 2.90#	F > NF,C
Toe clearance height (cm)	MAS¶,*	6.53 ± 1.19	6.30 ± 1.18	6.71 ± 1.18	7.93 ± 1.51	C > NF,F
	LAS¶,*	6.56 ± 1.17	6.42 ± 1.25	6.67 ± 1.12	7.70 ± 1.24	C > NF,F
ROM of hip joint (°)	MAS¶,*	26.44 ± 5.15	25.45 ± 5.92	27.22 ± 4.39	33.82 ± 7.44	C > NF,F
	LAS¶,*	26.74 ± 5.40	25.66 ± 5.55	27.59 ± 5.21	32.41 ± 5.33	C > NF,F
ROM of knee joint (°)	MAS¶,*	42.57 ± 7.24	40.02 ± 7.59	44.57 ± 6.37	53.07 ± 8.75	C > NF,F

	Direction	PD patients	Freezer (F)	Non-freezer (NF)	Control (C)	post-hoc
	LAS¶,*	42.63 ± 7.79	40.91 ± 8.32	43.98 ± 7.20	51.95 ± 8.79	C > NF,F
ROM of ankle joint (°)	MAS	19.13 ± 6.05	18.11 ± 7.31	19.93 ± 4.83	20.71 ± 5.33	ns
	LAS	18.23 ± 4.52	16.92 ± 4.05	19.25 ± 4.66	20.34 ± 4.46	ns
Maximum anti-phase (°)	MAS¶,*	15.49 ± 4.72	15.14 ± 4.14	15.77 ± 5.18#	22.40 ± 7.35	C > NF,F
	LAS¶,*	16.48 ± 5.92	15.20 ± 5.05	17.48 ± 6.42#	21.92 ± 6.34	C > F

All data are given as mean ± standard deviations. MAS: more affected side; LAS: less affected side; AI: asymmetry index; ROM: range of motion; ¶: Denotes significant difference between PD and control ($p < 0.05$); *: Denotes significant difference between freezer, non-freezer, and control ($p < 0.05$); #: Denotes significant difference between direction ($p < 0.05$).

The PD group took more steps and more time than the control group during 360^{o} turn for both directions (Table 4). The PD group also showed wider turning area and longer root mean square (RMS) distance than the control group. These differences with the control group were consistently found in the freezer group. The freezer group showed longer turning time for both directions and longer medio-lateral RMS distance for the MAS direction than the non-freezer group.

Table 4
Turning performance of participants

	Direction	PD patients	Freezer (F)	Non-freezer (NF)	Control (C)	post-hoc
Total steps	MAS¶,*	7.87 ± 2.29	8.76 ± 2.81	7.17 ± 1.49	6.52 ± 1.03	F,NF > C
	LAS¶,*	8.32 ± 2.88	9.51 ± 3.52	7.40 ± 1.84	6.05 ± 1.38	F,NF > C
Total time (s)	MAS¶,*	3.28 ± 1.03	3.65 ± 1.17	3.00 ± 0.82	2.58 ± 0.45	F > NF,C
	LAS¶,*	3.49 ± 1.25	3.96 ± 1.47	3.12 ± 0.91	2.36 ± 0.61	F > NF,C
Turning area (m^2)	MAS¶,*	2.03 ± 0.34	2.10 ± 0.36	1.98 ± 0.31	1.70 ± 0.17	F,NF > C
	LAS¶,*	2.03 ± 0.34	2.09 ± 0.37	1.98 ± 0.32	1.72 ± 0.38	F > C
AP-RMS distance (m)	MAS¶,*	0.17 ± 0.03	0.18 ± 0.04	0.16 ± 0.03	0.14 ± 0.03	F > C
	LAS¶,*	0.17 ± 0.04	0.17 ± 0.04	0.16 ± 0.03	0.14 ± 0.04	F > C
ML-RMS distance (m)	MAS¶,*	0.16 ± 0.03	0.16 ± 0.03	0.15 ± 0.03	0.13 ± 0.02	F > NF,C
	LAS¶,*	0.16 ± 0.03	0.16 ± 0.03	0.15 ± 0.03	0.13 ± 0.03	F > C

All data are given as mean ± standard deviations. MAS: more affected side; LAS: less affected side; AP: anterior-posterior; ML: medial-lateral; RMS: root mean square; ¶: Denotes significant difference between PD and control ($p < 0.05$); *: Denotes significant difference between freezer; non-freezer; and control ($p < 0.05$).

3. Correlation of freezing severity with clinical and gait characteristics of the freezer group

The score of new FoG questionnaire (NFoGQ) was positively correlated with symptom duration, LED, and HY stage of the freezer group during forward and backward walking (Supplementary table S3). It also showed a positive correlation with LED in the freezer group during 360°turning.

During forward walking, the NFoGQ score was correlated with step length, walking speed, toe clearance height, RoM of the hip joint, and AI of step length (Table 5). During backward walking, the NFoGQ score was correlated with step length, walking speed, and RoM of the knee joint. In the 360° turning, the NFoGQ scores were positively correlated with total steps in both direction, total step time in the less-affected side (LAS) direction. Negative correlation was found at step length, walking speed, and RoM of the knee joint

in both directions. RoM of hip and ankle joint and total time of turning in LAS direction, and toe clearance height in MAS direction also showed negative correlation with NFoGQ score.

Table 5
Correlation of the NFOGQ score with gait characteristics during forward and backward walking and turning

Step		MAS	LAS
Forward walking	Cadence	− .224	− .150
	Step time	.231	.122
	Step length	− .339*	− .356*
	Walking speed	− .339*	− .319*
	Toe clearance height	− .253*	− .337*
	ROM of hip joint	− .292*	− .252*
	ROM of knee joint	− .122	− .113
	ROM of ankle joint	− .234	− .036
	AI of step time	− .018	
	AI of step length	.328*	
Backward walking	Cadence	.212	.230
	Step time	− .191	− .243
	Step length	− .359*	− .263*
	Walking speed	− .301*	− .294*
	Toe clearance height	− .218	− .228
	ROM of hip joint	− .176	− .206
	ROM of knee joint	− .363*	− .284*
	ROM of ankle joint	− .050	.003
	AI of step time	.061	
	AI of step length	.230	
	Direction	MAS	LAS
360^{o} Turning	Cadence	.158	.173
	Step time	− .157	− .187
	Step length	− .362*	− .343*
	Walking speed	− .303*	− .271*
	AI of step time	− .095	− .040

Step		MAS	LAS
	AI of step length	.181	.252
	Toe clearance height	− .261*	− .190
	ROM of hip joint	− .236	− .276*
	ROM of knee joint	− .387*	− .347*
	ROM of ankle joint	− .082	− .297*
	Total steps	.318*	.319*
	Total time	.252	.275*
	Turning area	.157	.176
Pearson's correlation coefficient. *: $p < 0.05$.			

Discussion

In this study, patients with PD showed shorter step length, slower walking speed, and higher asymmetry of step length compared to control during forward and backward walking. During backward walking, there were more differences between PD and control groups, especially RoM of lower limb joints. These results are consistent with previous studies on forward and backward walking.[17,19,20,26]

Regarding FoG, several studies have found characteristics of freezers during forward walking.[8,11,25] Although freezers showed more prominent differences from the control group than non-freezers in our study, we found no significant difference between freezer and non-freezer during forward walking. However, freezers showed significant differences in step length and RoM of ankle joints during backward walking. One study of backward walking in PD patients has reported decreased RoM of multiple joints during backward walking and suggested that the ankle joint plays an imperative role in controlling the backward walking momentum.[26] Our previous study has also found that the impact of FoG is more prominent during backward walking than during forward walking.[27] These results suggest that the network controlling backward walking may be more vulnerable in PD patients, and the performance of backward walking of PD patients might be a key feature to show FoG characteristics. Our results revealed that differences between MAS and LAS step were only found in non-freezers for cadence and step time. This finding is unexpected because one study has suggested that PD patients with FoG show increased asymmetry between steps.[25] Indeed, AI of step length was increased by FoG both during forward and backward walking. Thus, asymmetry of temporal measures between steps might be a characteristic of PD and that loss of such asymmetry could be the impact of FoG in PD. Further studies are needed to clarify differences in spatial and temporal measures between steps. From our results of forward and backward walking, characteristics of FoG can be more sensitively captured during backward walking.

Kinematic measures can also be used for investigating characteristics of FoG in addition to spatial measures.

During 360^{o} turning, we found similar characteristics such as shorter step length, slower walking speed, higher AI of step length, and decreased RoM of lower limb joints during forward and backward walking. Turning performance was also decreased in PD patients as shown by increased total steps, time, and turning area during 360^{o} turning, consistent with previous studies.[28,29] Healthy elderly individuals use a pivoting strategy during turning movements.[7,12] Despite short step lengths of PD patients, they failed to perform stable turning steps, showing increased asymmetry between each in-step and out-step compared to the control group during natural pivot turning. Our previous study has reported decreased AI of step length of PD patients in approach steps of 180^{o} turning.[30] It would be different between approach step and turning step, and more difficult to perform 360^{o} than 180^{o} turning. Thus AI of step length could be a reliable characteristic of turning in PD patients as also shown by the difference between freezers and non-freezers. A previous study has reported that the freezer group shows slower step time, slower walking speed, and shorter step length than the non-freezer group during 180° turning.[31] We could only find a difference in asymmetry index of step length, although the freezer group showed increased total steps, time, and ML-RMS distance than the non-freezer group during 360^{o} turning. Our results might suggest that general turning performance would be better to demonstrate the impact of FoG than specific walking characteristics. The maximum anti-phase of the PD group was significantly smaller than that of the control group. These results indicate a decreased pelvic and shoulder rotation of PD patients possibly due to abnormal coordination of upper and lower body and axial rigidity. Slower thorax and pelvis turning onset and smaller head-to-pelvis angle of PD have been reported by a study of turning, which has demonstrated that axial rigidity in PD patients might reduce forward progression and increase lateral instability.[32] We also found increased AP- and ML-RMS distance in the PD group, especially in the freezer group, suggesting an increased axial instability during turning. The turning area was also greater in the PD group and the freezer group. There was a difference in the shape of tuning which was greater and more irregular in the order of freezer, non-freezer, and control (Fig. 1). These tendencies were more marked in the MAS direction in PD, although there was no significant difference at turning area or other characteristics according to turning direction in PD. Interestingly, the control group showed differences in step length, walking speed, and AI of step length according to turning direction. Although we could not find a difference according to turning direction in PD, loss of differences in walking characteristics and greater turning area and irregular turning trajectory in MAS direction could represent turning characteristics of PD, especially of FoG. These results suggest that it would be more efficient to turn to LAS direction for PD patients. Further studies are needed to confirm the difference according to turning direction between normal elderly and PD patients. Although few studies have investigated the turning area, one study has reported that PD patients display a larger radius than the control.[33] These turning difficulties in PD patients might be due to disrupted intersegmental coordination and automating complex movements since turning requires sequential coordination of segments.[7,33] Additionally, FoG might have more impact on intersegmental coordination as shown in our results.

We found significant correlations between the severity of FoG and walking characteristics in PD patients with FoG. As far as we know, this is the first study to report such correlation. Several studies have reported that spatio-temporal characteristics of walking are correlated with the severity of PD, such as UPDRS score and HY stage.[34,35] In the present study, the severity of FoG was correlated with step length, walking speed, and RoM of lower limb joints in all walking conditions. These correlations were most prominent during turning, which showed in all RoMs of lower limb joints and total steps and time of turning. However, there was no definite difference between steps or according to turning direction. Thus, FoG mainly impacted RoM and length characteristics during walking. The subjective severity of FOG could be a reliable indicator of severity of walking disturbance in PD patients with FoG, especially during turning.

This study has several limitations. During walking and turning tasks, we were unable to detect the actual number of FoG events. It is notoriously difficult to reproduce FoG in laboratory settings. We could rarely observe FoG events during experimental procedures, even in the defined “off” state. There was also a limitation in our study population because only subjects who could walk without assistance were selected. Additionally, our sample size was small, which could affect the generalizability of our results. Future studies with a larger sample size to capture FoG events in an actual daily environment are warranted to understand comprehensive walking characteristics and impacts of FoG under various walking and turning conditions.

Methods

A total of 68 PD patients were enrolled in this study. These patients were diagnosed with PD according to the UK Brain Bank criteria.[36] For forward and backward walking tests, five participants dropped out due to failure to perform the task or pain in lower limbs. Remaining participants were divided into freezer (n = 28) and non-freezer (n = 35) groups based on the presence or absence of FoG according to their responses to the new freezing of gait questionnaire (NFoGQ).[37] In case of the turning test, a total of 57 PD patients participated in this study. Eleven participants dropped out due to failure to perform the task, pain in the lower limbs, and deteriorating condition in ‘off’ state (Fig. 2). These participants were further grouped as freezers (n = 25) and non-freezers (n = 32). Fourteen healthy elderly individuals also participated in this study as a control group.

Participants with any impairment of lower limbs within six months prior to the testing, those who had difficulty in walking unassisted, and those who exhibited musculoskeletal and neurological symptoms affecting gait were excluded. Inclusion criteria for this study were: diagnosis of idiopathic PD according to the UK Brain Bank criteria, mild-to-moderate stage of patients walking independently, currently taking stable anti-PD medications over six months, and no dementia, which was defined as a score of ≤ 24 on the Mini-mental state exam (MMSE).[38] PD patients were tested at ‘defined off’ state. Experimental protocols were approved by the Institutional Review Board of Dong-A university Hospital and all methods were performed in accordance with the Declaration of Helsinki. All participants provided written informed consent prior to their participation in the study.

Forward and backward walking and turning tests were captured using six infrared cameras (Vicon, MX-T10, UK) on an 8-meter walkway, as in our previous study.[27] A global coordinate system was established, with the positive X-axis to the right, positive Y-axis facing anteriorly, and the Z-axis defined as the cross-product between the X-axis and the Y-axis, with the positive Z-axis facing superiorly. Weight, height, shoulder offset, elbow width, wrist width, hand thickness, leg length, knee width, and ankle width were measured bilaterally for all participants to obtain joint kinematic data. A 39-marker plug-in-gait model with 14 mm spherical reflective markers placed according to the modified Helen Hayes marker set was used. Markers were attached on the clavicle, sternum, the 7th cervical vertebrae, the 10th thoracic vertebrae, scapular medial border, and bilaterally on the front and back of the head, shoulder, lower third of the upper arm, lateral humeral epicondyle, lower third of the forearm, medial and lateral styloid processes of the wrist, the 3rd metacarpal head, anterior superior iliac spine, posterior superior iliac spine, lower third of the lateral thigh, lateral femoral epicondyle, lower third of the lateral shank, calcaneus, lateral malleolus, and the second metatarsal head. These markers were secured with athletic tape to reduce motion artifacts. The sampling frequency for kinematic data was set at 100 Hz. Collected data were filtered using digital low-pass filters (second-order Butterworth filters) at 6 Hz. Motion data capture and post-processing of marker trajectories were performed using Nexus software (version 1.83, VICON, UK).

All participants performed forward and backward walking tests. They were asked to walk in forward and backward directions at their preferred speed. In case of 360° turning test, participants were asked to turn in left and right directions at their preferred speed. The start of turning was set as the pelvis rotation angle by 10° in the global coordinate system. The end of turning was set as the pelvis rotation angle by 350°. Three successful complete trials in forward and backward walking and turning tests were captured for each participant. Walking step was defined as two steps after the third step during the walking task. Each step and turning direction were divided according to more-affected side (MAS) and less-affected side (LAS). The control group exhibited a preponderance of right-hand dominance. Thus, the MAS for controls was taken to be the left side.

Spatio-temporal characteristics were analyzed using walking speed, step time, step length, stride time, stride length, and asymmetry index (AI) of step time and length during forward and backward walking. Additionally, total steps, total step time, walking speed, step time, step length, stride time, stride length, and AI of step time and length during turning were determined. AI was defined as observed asymmetry between MAS and LAS steps using maximum and minimum values of step time and length. The longest step time and length were considered as the maximum amplitude, whereas the shortest step time and length were taken as the minimum amplitude.[25]

$$\frac{\text{Max. amplitude} - \text{Min. amplitude}}{\text{Max. amplitude}} \text{ X } 100$$

Kinematic characteristics of walking was analyzed through RoM of lower limb joints, maximum anti-phase, and trajectory and area of 360^{o} turning. RoMs of the hip, knee, and ankle in the sagittal plane were identified. RoM was calculated as the difference between the maximum and minimum joint angles during a single gait cycle. Toe clearance height was measured as the maximum vertical height of the toe marker during the swing phase of each step. The maximum anti-phase was calculated as the maximum angle between the pelvic vector (from left marker to right marker of the anterior superior iliac spine) and the shoulder vector (from left marker to right marker of the shoulder) in the horizontal plane during turning. Turning area, antero-posterior root mean square (AP-RMS) distance, and medio-lateral root mean square (ML-RMS) distance were calculated using the path of center of mass (CoM) during turning. Turning area was defined and calculated as 95% ellipse area of turning.[39] AP- and ML-RMS distances were defined as diameters in AP and ML direction, respectively.

All statistical analyses were performed using SPSS version 21.0 (SPSS Inc., Chicago, IL, USA). Descriptive statistical analysis was utilized to describe characteristics of each variable using mean and standard deviation. Shapiro-Wilk test was used to confirm normality. Two-way repeated analysis of variance (ANOVA) was conducted to compare differences between groups and compare results within different steps or directions. In addition, Scheffe post-hoc test was used in one-way ANOVA between groups. T-test was conducted for paired samples between MAS and LAS steps in forward and backward walking tests and MAS and LAS direction in the turning test. For the association of NFoGQ and other symptom scales with spatio-temporal and kinematic variables during forward and backward walking and turning tests, Pearson correlation coefficient was used. Significance was set at $p < 0.05$.

Declarations

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Author contributions

S.C. and M.S. conceptualized the study, and S.C., M.S., C.Y., and J.W.K. collected the data. M.S. and S.C. performed the statistical analysis, S.C., M.S. and C.Y. interpreted the data, and M.S. and S.C. wrote the main manuscript. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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Figures

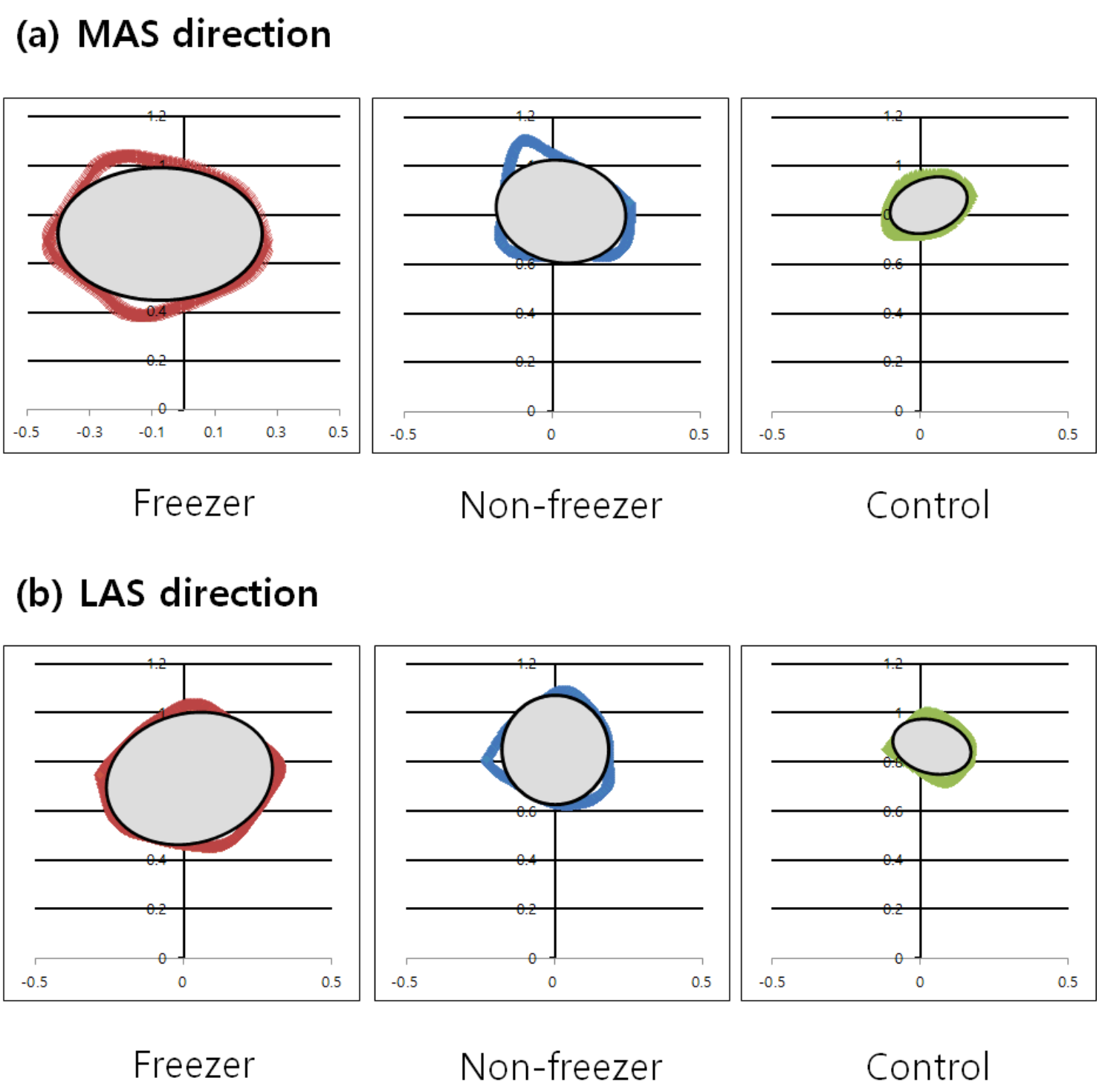

Figure 1

Turning area of groups according to the turning direction.

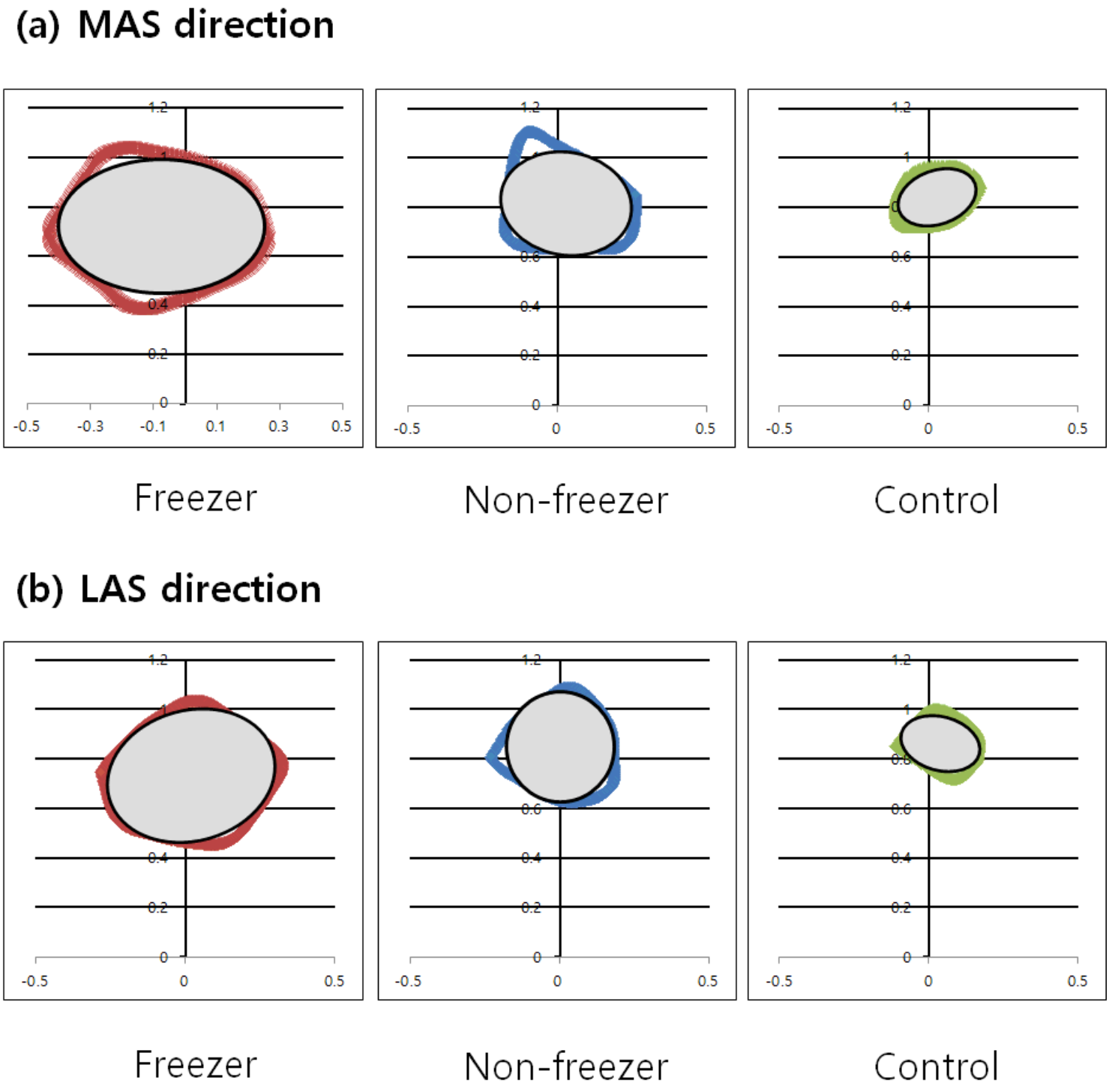

Figure 1

Turning area of groups according to the turning direction.

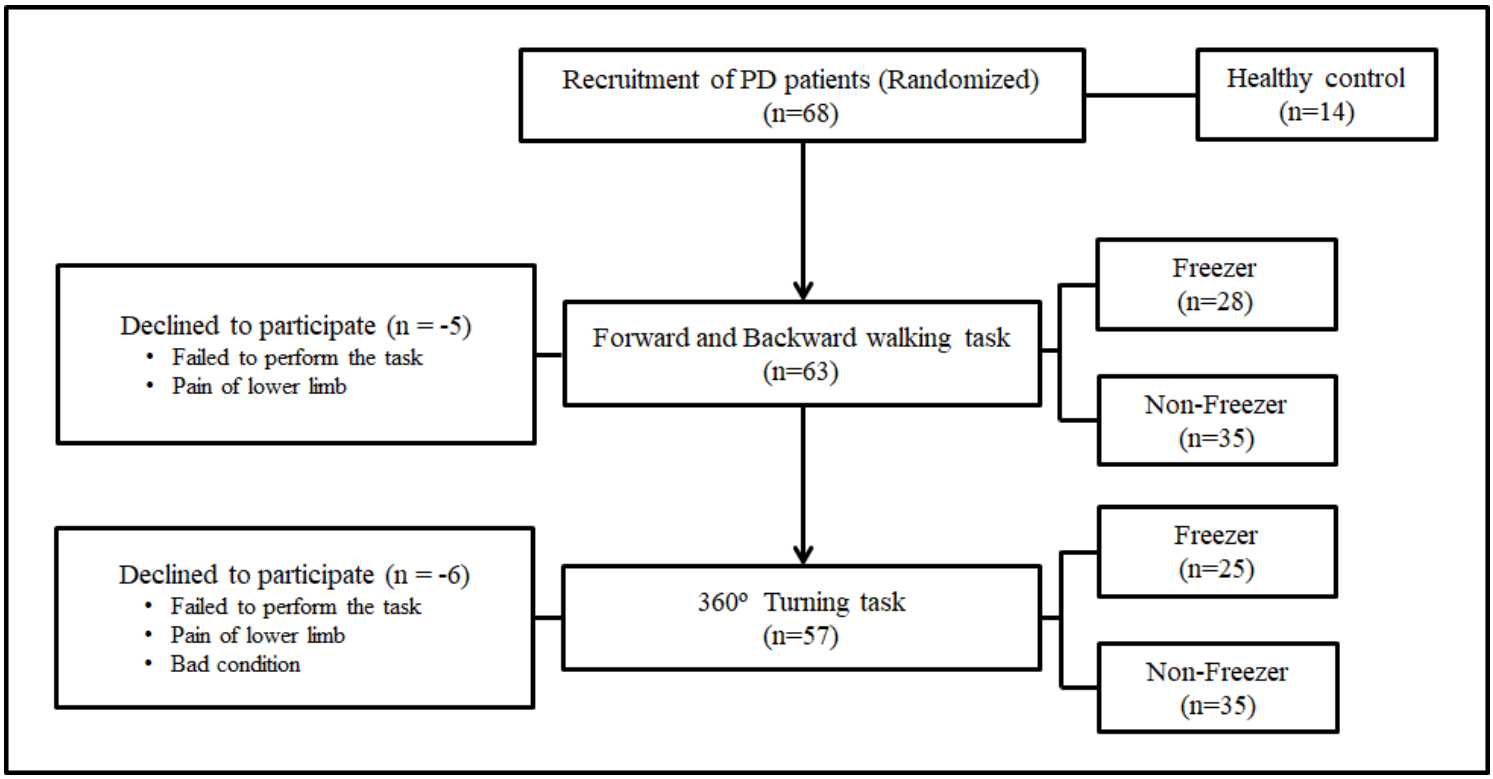

Figure 2

Consort flow chart.

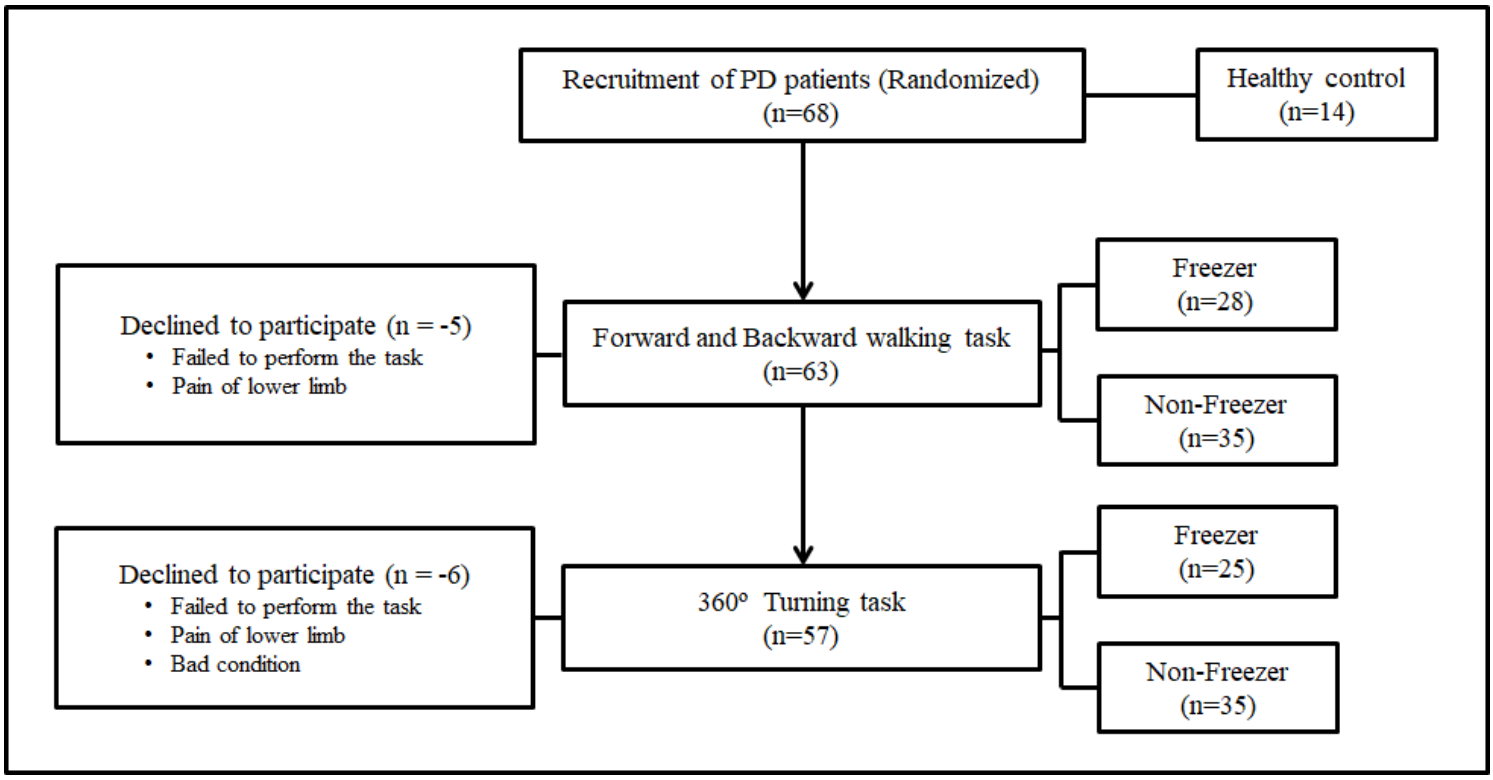

Figure 2

Consort flow chart.

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