Gait & Posture 74 (2019) 187–193

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Objective measures to investigate turning impairments and freezing of gait in people with Parkinson's disease

Matilde Bertoli[a,b,*], Ugo Della Croce[a,b], Andrea Cereatti[a,b], Martina Mancini[d]

[a] Department of Biomedical Sciences, University of Sassari, Sassari, Italy
[b] Interuniversity Centre of Bioengineering of the Human Neuromusculoskeletal System, Sassari, Italy
[d] Department of Neurology, Oregon Health & Science University, Portland, OR, United States

ARTICLE INFO

Keywords:
Turning
Inertial measurement unit
Parkinson's disease
Freezing of gait
Dual-task

ABSTRACT

Background: Turning is impaired in people with Parkinson's Disease (PD) and it is a common trigger for freezing of gait (FoG). Recent evidence suggests that people with PD who freeze (PD + FoG) have worse turning performance than those who don't have freezing (non-freezers, PD-FoG), and the freezing episodes are exacerbated by increasing the turn angular amplitude.

Research question: We investigated the difference between turning 180° while walking versus turning 360° in place, in both single- and dual-task conditions, by means of objective measures in people with PD with and without FoG.

Methods: Twenty-four PD + FoG and eighteen PD-FoG performed 180° turns while walking and 360° turns in place during single- and dual-task conditions. Quantitative measures of turning and the dual-task cost were computed. Differences were investigated between groups and within turning types using ANOVA. Associations between turn measures and clinical scales were examined with Spearman correlations.

Results: Turn duration and the number of steps were greater, and peak angular velocity slower, in PD + FoG compared to PD-FoG ($p < 0.001$). Dual-task costs were similar across groups, but turn duration showed significant interaction ($p = 0.03$). Posture Instability and Gait Disability (PIGD) subscore was associated with all turn measures in PD-FoG; whereas PIGD was mainly associated with turning while walking in PD + FoG.

Significance: Objective measures of turning revealed differences between people with and without FoG, specifically, people with FoG showed more impairments in 360° turning in place compared to 180° turning while walking. However, as the turning challenges were increased by adding a dual-task, results from PD + FoG were similar to those from PD-FoG.

1. Introduction

Parkinson's disease (PD) is one of the most common neurodegenerative disorders [1]. Over 80% of people with PD eventually develop freezing of gait (FoG), a sudden and transient failure to initiate or maintain locomotion [2]. FoG is an episodic phenomenon of controversial pathophysiology, and the episodes are usually triggered by specific situations, for example turning, crowded spaces, initiating walking, walking through narrow passages, or approaching a destination [3,4].

Besides specific motor tasks, another common trigger for FoG is the addition of a concurrent cognitive challenge while walking or turning, often referred as a dual-task (DT). In fact, the addition of a concurrent cognitive challenge has been found to further impair the motor performance in people with PD and FoG (PD + FoG) compared to people with PD who do not experience FoG (PD-FoG) [5]. Specifically, recent studies showed that the DT cost for stride length, cadence and gait speed during straight walking was significantly increased in PD + FoG compared to PD-FoG [6–10]. However, the impact of DT on turning performance in PD + FoG is still controversial and turning may be a stronger trigger for FoG than DT [8]. Spildooren et al. found a significant increase of the number of FoG episodes when turning while walking with a DT, but only for 360° turns, not during 180° turns [8]. In addition, DeSouza et al., showed no differences in objective measures of 180° turning while walking (duration and peak velocity) during single-task turning compared to dual-task turning in PD + FoG [6].

Interestingly, the amplitude of turning seems to play a role in eliciting FoG, at least in the clinic or laboratory settings, where FoG episodes occur more rarely than in daily life [1,2,4,11]. In fact, it has been described that the execution of sharper turns while walking,

* Corresponding author at: Department of Biomedical Sciences, University of Sassari, Sassari, Italy.
E-mail address: mbertoli@uniss.it (M. Bertoli).

https://doi.org/10.1016/j.gaitpost.2019.09.001
Received 12 December 2018; Received in revised form 1 August 2019; Accepted 1 September 2019

characterized by a smaller turning radii and greater angular amplitude, tend to elicit more freezing episodes compared to turns at smaller angles, decreasing turning angle or increasing turning arc length [8,11,12]. Specifically, Mancini and colleagues, and Snijders and colleagues, showed that repeated 360° turns in place were more effective in eliciting FoG compared to 180° or 360° turns while walking [4,13]. A recent systematic review, focused on the differences in turning between PD + FoG and PD-FoG, shows that PD + FoG, in the absence of FoG episodes, take longer to turn, have a lower turn peak velocity, and take more steps to turn at a higher cadence compared to PD-FoG [14]. Although the comparison between different tasks, such as turning 360° in place and 180° while walking may seem obvious, since many reports excluded turns with the presence of FoG from analysis, it is still unclear which combination of turns (180° or 360°) and task (single- or dual-task) would increase FoG occurrence and why that would be. In addition, small evidence exists on which behavioral characteristics of turning and which turn amplitude would differ the most among PD + FoG and PD-FoG even in absence of FoG.

As turning is thought to require more coupling of posture and stepping, and more cognitive control compared to straight ahead gait [7,15,16], we expect that 360° turning in place with a cognitive challenge would be more difficult for PD + FoG than PD-FoG, and that the DT condition would elicit more freezing episodes in PD + FoG than single task condition. Therefore, our aims were: 1) to quantify and compare kinematic differences in PD + FoG and PD-FoG while performing both 180° turning while walking and 360° turning in place, and 2) to determine whether a concurrent dual task similarly impacts the two different turning tasks in PD + FoG and PD-FoG.

2. Methods

2.1. Participants

Forty-two subjects with idiopathic PD were recruited through the Parkinson's Center of Oregon clinic at Oregon Health & Science University (OHSU). Based on the first question of the New FoG Questionnaire (NFOG-Q) [17] -"Have you experienced FoG in the past month?"- PD subjects were divided in two groups. Twenty-four subjects (19 M, 5 F) answered 'yes' and were classified as freezers (PD + FoG), while eighteen subjects (14 M, 4 F) answered no, and were assigned to the non-freezers (PD-FoG) group. Subjects' characteristics and clinical scores are reported in Table 1.

Inclusion criteria were: diagnosis of idiopathic PD with sensitivity to levodopa and off-medication Hoehn & Yahr scores of II-IV. Exclusion criteria: Other factors affecting gait (e.g., hip replacement, musculoskeletal disorder, uncorrected vision or vestibular problem), inability to stand or walk for 2 min at a time, or inability to follow instructions.

All participants provided informed written consent to the protocol approved by the OHSU Institutional Review Board.

Table 1
Subjects characteristics in people with PD with (PD + FoG) and without (PD-FoG) Freezing of Gait (Mean ± STD).

	PD-FOG	PD + FOG	*p-value*
Age (years)	70.3 ± 6.8	69.2 ± 7.1	
Gender	14 M 4 F	19 M 5 F	
NFoG - Q (score)	–	16.5 ± 6.0	
Disease Duration (years)	7.7 ± 4.3	8.7 ± 6.2	0.58
MDS-UPDRS III	43.6 ± 11.3	45.8 ± 12.1	0.56
PIGD subscore	3.8 ± 2.5	7.6 ± 3.7	< 0.01
MoCA	26.2 ± 3.3	24.9 ± 4.9	0.35

p-value is reported for *t*-test between PD + FoG and PD-FoG.

2.2. Procedures

All the participants were tested in the practical defined OFF state (after withdrawing their antiparkinsonian medication for at least 12 h), since FoG occurs more in the OFF levodopa medication. A trained examiner (MM) administered the motor section (Part III) of the MDS-UPDRS [18] to rate disease severity. The Posture Instability and Gait Disability (PIGD) sub-score was also calculated from the MDS-UPDRS Part III [19]. The Montreal Cognitive Assessment (MoCA) was used to assess general cognition [20], and the perceived severity of FoG was recorded by means of the NFOG-Q [17].

Participants performed a series of motor tasks while wearing three inertial sensors (Opals - APDM, Inc.) positioned on both feet (dorsally) and on the back (approximately at the level of L5). Each individual was asked to perform the following trials sequentially: i) 360° turning in place, single task, consisting of alternating 360° axial rotations clockwise and counter-clockwise for one minute; ii) 360° turning in place with a dual-task; iii) 180° turning while walking, as part of a two minutes long walk, where the subjects walked straight ahead for 7 m at a comfortable speed, turned around and continued walking in the opposite direction continuously for two minutes; iv) 180° turning while walking with a dual-task.

The concurrent dual tasks used for turning in place and turning while walking were different to avoid potential learning effects. Specifically, for turning in place the dual-task consisted in serial subtractions by 3 s, while for turning while walking the dual-task consisted in reciting the alphabet skipping every other letter (A, C, E, etc.). In the DT condition, no instructions were given on whether to pay more attention to the motor or cognitive task.

The signals from the Opal units were recorded at 128 Hz, streamed wirelessly to a laptop and stored for subsequent offline analysis with Matlab (MathWorks. R2016a).

2.3. Data analysis

For the present analysis, we focused only on the first turn for all trials to avoid mixing the first turn with compensatory strategies that participants might adopt in the following turns. Data from the three sensors were processed separately for each trial in order to automatically identify the turning tasks. Detailed procedure to extract turns are described in [21]. Briefly, for the turning while walking task, a threshold approach on the low-pass filtered (Butterworth, 15 Hz) vertical angular velocity recorded on the low back determined instants of turn beginning and ending [22]. For the turning in place task, a method based on magnetometer readings and angular velocity (lower back sensor) was implemented: low-pass filtered (Butterworth, 1 Hz) planar components of the magnetometer signals were used to detect an inversion of the local magnetic field and thus isolate a turn. For each detected turn, the preceding and following zero-crossings of the filtered, offset-free vertical angular velocity were used as turn beginning and ending instants.

Then, the following quantitative measures were computed for the first turn in each trial: - Turn Duration (s), calculated as the interval of time from the beginning to the ending of the turn; - Number of Steps, combined right and left steps during the turn [23]; - Turn Peak Velocity (degrees/s), calculated as the maximum peak amplitude in the vertical angular velocity; - Turn Jerk (Integrated squared jerk, m^2/s^5), calculated as the integral of the squared time derivative of the linear acceleration, used to quantify fluidity of turning in both anteroposterior (AP) and mediolateral (ML) directions; and - Turn Range of acceleration (m/s^2), calculated as the difference between maximum and minimum linear acceleration for both ML and AP directions.

The dual-task cost (DT cost) was calculated as DT cost [%] = 100* (DT turning measure – ST turning measure) / ST turning measure.

The video recordings of the trials were reviewed to assess presence of FoG by a trained researcher (MM) blinded to group allocation.

Participants' FoG severity was rated according to the criteria described by Schaafsma et al. [24].

2.4. Statistical analyses

A two-way (groups × turns) repeated measures analysis of variance (ANOVA) was used to investigate the difference in objective measures between groups (PD + FoG/PD-FoG) and within turning tasks (180° while walking/360° in place). Since turn jerk, turn duration and step number distributions were not normally distributed, for the ANOVA analysis the data were transformed into logarithmic scale. Similarly, a two-way ANOVA was used to investigate the difference in DT cost between groups (PD + FoG/PD-FoG) and within turn tasks (180° while walking/360° in place). In addition, for the PD + FoG group, turn measures obtained in trials with observed FoG were compared to those obtained in trials without FoG episodes by means of a *t*-test (for all turning tasks except for 360° in place DT condition, due to unbalanced distributions).

Non-parametric (Spearman) correlations were performed to investigate the associations between objective measures of turning and clinical scales. Correlation analyses were run considering the two groups both separately and together. Statistical significance was set at $p < 0.05$. SPSS (IBM V.23) was used to run statistical analyses.

3. Results

3.1. Turning characteristics for 180° turning while walking and 360° turning in place in PD + FoG and PD-FoG

As expected, turn duration was longer for the 360° turning in place compared to the 180° turning while walking in both PD + FoG and PD-FoG (significant turn effect: $F = 159.22$, $p < 0.001$). PD + FoG took a longer time to complete both turns compared to PD-FoG (group effect: $F = 18.62$, $p < 0.001$), see Table 2 and Fig. 1. In addition, the significant interaction effect on turn duration ($F = 6.68$, $p = 0.01$) indicates that the increase in turn duration in the 360° turn compared to 180° while walking was different in PD + FoG compared to PD-FoG.

The number of steps showed similar significant results, specifically: i) a significant difference between groups ($F = 19.38$, $p < 0.001$) with PD + FoG taking more steps compared to PD-FoG; ii) a significant difference in turning task ($F = 159.23$, $p < 0.001$), with the turning in place requiring more steps than turning while walking; iii) a significant interaction effect ($F = 9.37$, $p < 0.001$) with PD + FoG requiring significantly more steps in the 360° turning in place than 180° turning while walking compared to PD-FoG.

In addition, PD + FoG group had lower peak velocity to perform both turn types compared to PD-FoG (group effect: $F = 14.67$, $p < 0.001$), Table 2 and Fig. 1.

The anteroposterior range of acceleration while turning was similar in PD-FoG and PD + FoG ($F = 2.69$, $p = 0.11$), however, it was significantly lower for the turning in place compared to turning while walking ($F = 7.87$, $p = 0.01$) Table 2 and Fig. 1. Likewise, the mediolateral range of acceleration while turning was similar in PD-FoG and PD + FoG and, even though the mediolateral range of acceleration was larger during turning in place compared to turning while walking in PD + FoG, there was no statistically significant interaction ($F = 0.30$, $p = 0.59$).

Lastly, turn jerk was similar across groups, but showed an increase from turning 180° while walking to turning 360° in place both in anteroposterior ($F = 5.08$, $p = 0.03$) and mediolateral directions ($F = 29.12$, $p < 0.001$); see Table 2 and Fig. 1. The increase approached significance, only in the PD + FoG group, in the anteroposterior ($F = 3.62$, $p = 0.07$) direction, but not in the mediolateral ($F = 1.17$, $p = 0.29$) direction.

3.2. DT cost effects on turning in PD + FoG and PD-FoG

The DT cost of turn duration, number of steps, and turn peak velocity showed significant differences for the turning in place compared to the turning while walking. In fact, both PD + FoG and PD-FoG took longer time, more steps, and slower peak velocity for the 360° turning in place compared to 180° turning while walking (Table 3 and Fig. 2). In addition, the increase in DT cost from turning while walking to turning in place was larger in PD + FoG compared to PD-FoG, as showed by the significant interaction effect ($F = 4.97$, $p = 0.03$):

3.3. Associations between disease severity and quantitative measures of turning

Correlations are detailed in Tables 4–6, supplementary material, and a visual representation is depicted in Fig. 3. In the PD-FoG group, the MDS-UPDRS III was not correlated to any measure for the turning while walking task; while a higher (worse) MDS-UPDRS III was associated with longer turn duration and greater number of steps for the turning in place in place task ($r > 0.55$, $p < 0.02$). In the PD + FoG group, a higher (worse) MDS-UPDRS III was associated with lower turn peak velocity, higher turn duration, lower mediolateral and anteroposterior jerk and smaller mediolateral range of acceleration for turning while walking ($r > 0.44$, $p < 0.04$); while it was not correlated to any measure in the turning in place task.

In the PD-FoG group, the PIGD subscore was correlated to all the turning measures ($r > 0.51$, $p < 0.04$) for both the turning tasks;

Table 2
Differences in turning performance in PD + FoG and PD-FoG for the two tasks (180° turn while walking and 360° turn in place).

		Turn while walking	*Turn in place*	Group		Turn		Interaction	
		Mean ± sd	Mean ± sd	F-value	p-value	F-value	p-value	F-value	p-value
Turn Duration (s)	PD-FoG	2.55 ± 0.58	5.33 ± 3.88	18.62	< ***0.001***	159.22	< ***0.001***	6.68	***0.01***
	PD + FoG	3.20 ± 0.75	8.45 ± 4.22						
Number of Steps (N)	PD-FoG	5.24 ± 1.18	9.92 ± 3.40	19.38	< ***0.001***	159.23	< ***0.001***	9.37	< ***0.001***
	PD + FoG	6.41 ± 1.31	19.48 ± 10.00						
Peak Velocity (degrees/s)	PD-FoG	143.87 ± 26.18	140.30 ± 40.87	14.67	< ***0.001***	0.01	0.91	0.28	0.60
	PD + FoG	106.77 ± 26.61	106.03 ± 30.62						
ML Range (m/s^2)	PD-FoG	5.31 ± 1.64	5.09 ± 1.81	0.01	0.94	0.01	0.94	0.30	0.59
	PD + FoG	5.14 ± 1.52	5.45 ± 1.78						
AP Range (m/s^2)	PD-FoG	4.49 ± 1.46	3.70 ± 1.34	2.69	0.11	7.87	***0.01***	0.41	0.52
	PD + FoG	3.77 ± 1.09	3.48 ± 0.94						
ML Jerk (m^2/s^5)	PD-FoG	3.43 ± 2.72	6.05 ± 5.90	0.80	0.38	29.12	< ***0.001***	1.17	0.29
	PD + FoG	4.01 ± 3.74	9.58 ± 9.36						
AP Jerk (m^2/s^5)	PD-FoG	2.06 ± 1.80	2.36 ± 2.12	0.34	0.56	5.08	***0.03***	3.62	0.07
	PD + FoG	1.71 ± 1.17	4.57 ± 5.60						

Significant differences ($p < 0.05$) for the ANOVA results are indicated in bold.

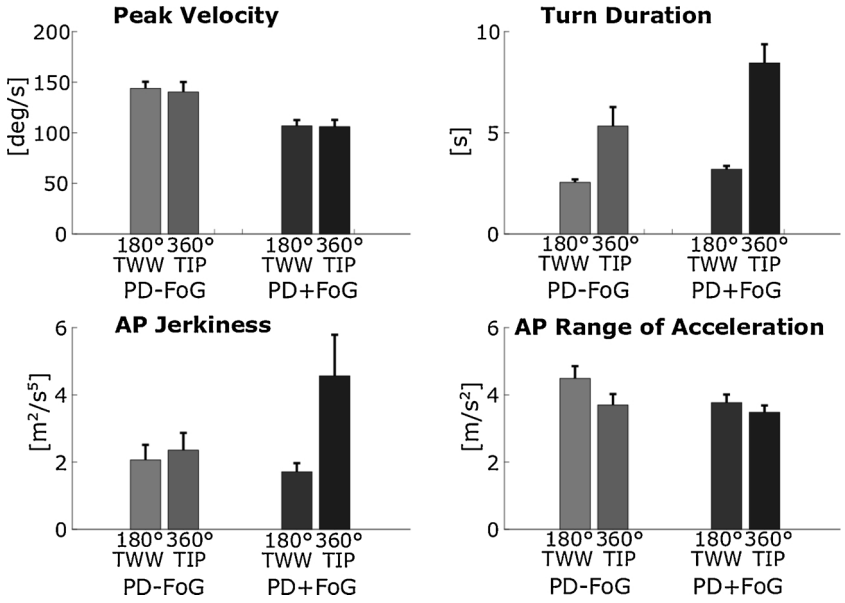

Fig. 1. Mean and SEM of the objective measures in the single task condition for PD-FoG and PD + FoG (Turning while walking, 180° TWW; Turning in place, 360° TIP).
AP = anteroposterior; deg = degrees, s = seconds, m = meters.

specifically, a higher PIGD subscore was associated with longer turn duration, greater number of steps, and lower turn peak velocity, jerk and range of acceleration. Instead, in the PD + FoG group, a higher PIGD subscore was significantly associated to longer turn duration, greater number of steps, lower turn peak velocity, smaller range of anteroposterior and mediolateral acceleration and lower mediolateral jerk in the turning while walking task ($r > 0.44$, $p < 0.04$); while it was associated with turn duration only for the turning in place ($r = 0.51$, $p = 0.02$).

Lastly, disease duration was not associated to any turning measure.

3.4. Turning characteristics in trials with and without observed FoG

During the turning while walking task, 6 out of 23 individuals in the PD + FoG group showed freezing in the single-task condition and 8 out of 23 showed freezing in the dual-task condition. One participant did not allow video recordings, therefore we were not able to identify the FOG episodes. Comparison are detailed in Table 7, supplementary material.

Overall, the objective measures of turning while walking were similar in the trials with and without observed FoG.

During turning in place, freezing was observed in 15 PD + FoG in the single-task conditions and in 19 for the dual-task conditions. For the single task turning in place, the number of steps, but not the turn duration, was significantly larger in trials with observed FoG than in trials without FoG episodes ($p = 0.01$). Also, the mediolateral range of acceleration ($p = 0.02$) and the mediolateral and anteroposterior jerk ($p = 0.02$ and $p = 0.04$, respectively) were greater for trials with observed FoG compared to the trials without FoG.

4. Discussion

This study aimed to characterize, by means of wearable inertial sensors, 180° turning while walking and 360° turning in place in subjects with PD with and without FoG and to investigate the changes in turning performance with the addition of a concurrent dual task while turning. In addition, we determined the association between disease severity, measured by the MDS-UPDRS III and the PIGD, and quantitative measures of turning. Lastly we compared turning characteristics between trials with and without observed FoG.

Table 3
Dual task cost differences of turning performance in PD + FoG and PD-FoG for the two tasks (180° turn while walking and 360° turn in place).

		Turn while walking	*Turn in place*	Group		Turn		Interaction	
		Mean ± sd	Mean ± sd	F-value	p-value	F-value	p-value	F-value	p-value
Turn Duration (s)	PD-FoG	13.76 ± 22.03	23.69 ± 22.96	0.85	0.36	16.97	< ***0.001***	4.97	***0.03***
	PD + FoG	8.01 ± 19.06	53.86 ± 70.00						
Number of Steps (N)	PD-FoG	3.84 ± 15.94	20.78 ± 28.71	0.06	0.81	8.76	***0.01***	0.47	0.50
	PD + FoG	4.00 ± 27.10	26.24 ± 35.60						
Peak Velocity (degrees/s)	PD-FoG	−6.78 ± 13.29	−14.01 ± 11.65	0.68	0.42	12.19	< ***0.001***	3.43	0.07
	PD + FoG	−4.42 ± 19.67	−21.84 ± 20.30						
ML Range (m/s^2)	PD-FoG	−6.47 ± 16.96	−8.71 ± 11.64	0.41	0.53	2.83	0.10	0.74	0.40
	PD + FoG	−8.31 ± 17.65	−14.14 ± 26.55						
AP Range (m/s^2)	PD-FoG	−6.87 ± 24.47	−8.89 ± 16.74	0.40	0.53	0.49	0.49	0.20	0.66
	PD + FoG	−7.88 ± 36.65	−15.24 ± 18.81						
ML Jerk (m^2/s^5)	PD-FoG	−0.54 ± 33.45	5.56 ± 52.92	0.07	0.80	0.01	0.91	0.08	0.77
	PD + FoG	1.73 ± 56.30	3.36 ± 56.60						
AP Jerk (m^2/s^5)	PD-FoG	−19.54 ± 27.06	5.44 ± 46.87	0.24	0.63	2.13	0.15	0.01	0.92
	PD + FoG	−1.14 ± 92.93	6.62 ± 58.06						

Significant differences ($p < 0.05$) for the ANOVA results are indicated in bold.

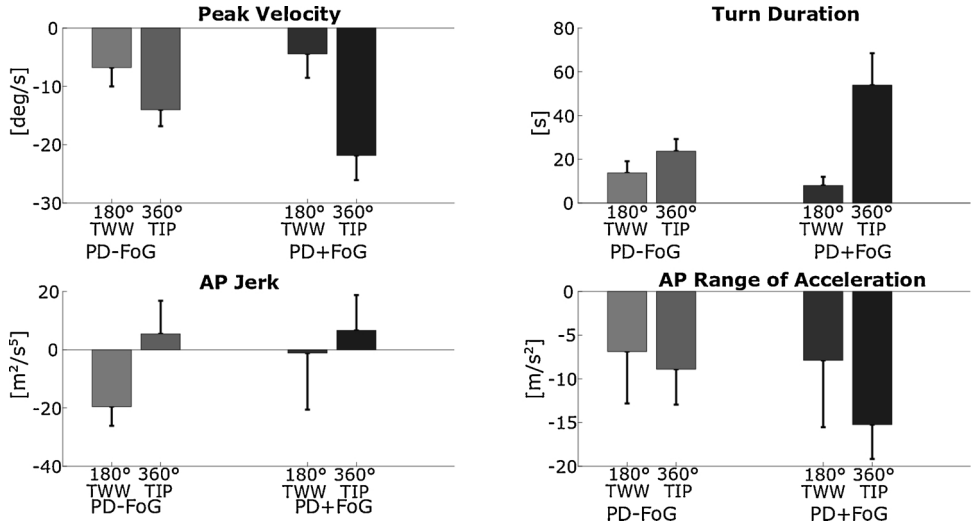

Fig. 2. Mean and SEM of the objective measures, dual-task cost in PD-FoG and PD + FoG (Turning while walking, 180° TWW; Turning in place, 360° TIP).

4.1. Turning differences between 180° turning while walking and 360° turning in place

When summarizing differences between PD + FoG and PD-FoG, we found that PD + FoG took generally longer time to turn, turned at slower peak velocity and needed more steps to complete a turn, but showed similar range of acceleration during turning and a tendency for higher jerk compared to PD-FoG. Our findings are in keeping with the previous literature for the 180° turning while walking [6], however, for the 360° turning in place, here we showed that peak velocity is significantly lower in PD + FoG compared to PD-FoG, in partial disagreement with previous findings [13], where this decrement did not reach significance, even though a trend was observed. The range of acceleration while turning was similar in the two groups, as previously found by [25] for mediolateral range. Similarly, a recent manuscript [26] showed that the center of mass velocity did not show clear differences between PD + FoG and PD-FoG during 180° turning while walking.

In both groups, as expected, 360° turning in place required longer time and higher number of steps compared to 180° turning while walking, but interestingly, similar peak velocity. The range of acceleration was also similar in both turning tasks in the mediolateral direction, but greater for turning while walking in the anteroposterior direction compared to turning in place. In addition, turning jerk was greater during turning in place compared to turning while walking in both the anteroposterior and mediolateral direction. While some of these differences were observed in both PD-FoG and PD + FoG, turn duration and number of steps showed a significant interaction effect, suggesting that PD + FoG show further impairments when turning in place compared to turning while walking compared to PD-FoG.

These findings are in keeping with other studies showing that PD + FoG have more difficulties during turning in place compared to turning while walking [8,14]. This result may partly be due the PD + FoG group having more freezing episodes during the turning in place task compared to the turning while walking task, resulting in an increase in number of steps needed to complete the task.

The greater anteroposterior range of acceleration in 180° turning while walking compared to 360° turning in place could be due the intrinsic characteristics of the turning tasks, since in the turning while walking the subjects may be preparing to walk forward exiting from the turn. In addition, turning jerk was higher for the turning in place compared to the turning while walking task. In Mancini et al [24], that measured turning in daily life, jerk and range of acceleration also did not show any significant group x turn amplitude interaction, but an interaction effect emerged when analyzing the coefficients of variation. In the present study, to be more consistent across turning tasks, we only analyzed the first turn and therefore we could not compute the coefficient of variation, that may have provided further insights.

4.2. DT cost effects on turning among PD + FoG and PD-FoG

Our findings suggest that turning in place may require a greater cognitive effort compared to turning while walking, as indicated by the greater DT cost of turn duration, number of steps and peak velocity for the turning in place compared to turning while walking in both groups. Additionally, the increase in DT cost of turn duration (and almost in peak velocity) from turning while walking to turning in place was greater in PD + FoG compared to PD-FoG (interaction effects). This result supports our hypothesis that turning in place with a cognitive challenge would be more difficult in PD + FoG compared to PD-FoG. In keeping with previous studies [6], our results showed that the DT cost alone did not show a group effect.

4.3. Associations between disease severity and quantitative measures of turning

The associations with clinical outcomes showed that worse severity in the PIGD subscore, but not in the MDS-UPDRS part III or disease duration, was significantly associated to worse turning performance in the PD-FoG group, only for turning while walking. Interestingly, such results were only partially replicated in the PD-FoG group. These results highlight that the severity of axial symptoms and gait difficulties (reflected in the PIGD subscore), and not the general severity of the disease, have a direct impact on turning performance. Lastly, freezing may be adding a different component to turning deficits not necessarily associated to severity of axial symptoms.

4.4. Turning characteristics in trials with and without FoG in the PD + FoG group

Interestingly, the objective measures of turning while walking were similar in trials with and without freezing episodes. Instead, we would have expected some differences, specifically, we would expect turning duration to be longer in those trials where freezing was observed. The addition of the dual task lead to the same result for turning while walking. However, for the turning in place, we observed significant differences, specifically in the number of steps, in trials with FoG compared to trial without FoG. These findings confirm previous work showing that turning in place may pose additional difficulties compared

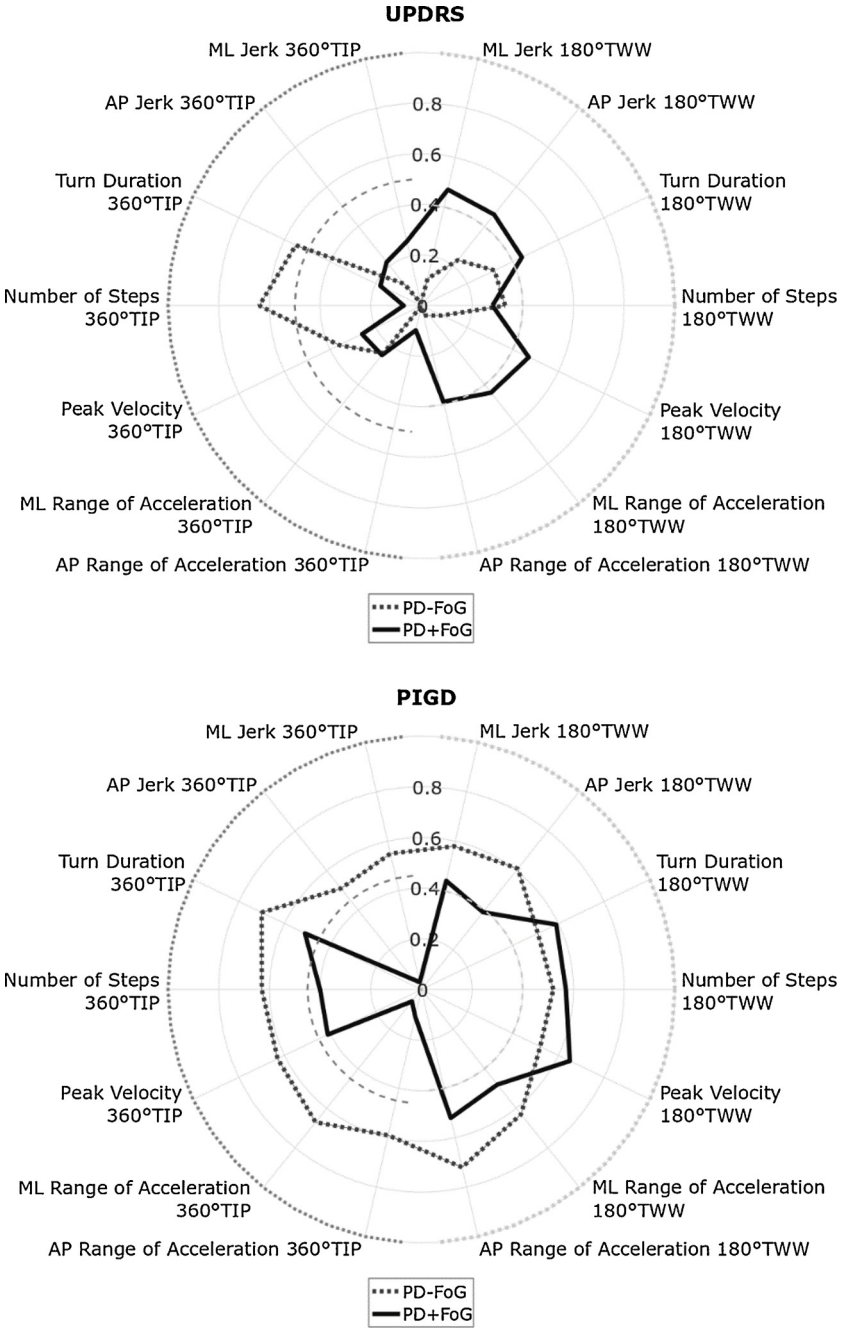

Fig. 3. Spider plots comparing Spearman correlations of the clinical scores with objective measures during turning while walking (180° TWW, on the right) and turning in place (360° TIP, on the left) for PD + FoG and PD-FoG. Dashed semicircles delimit significance.

to turning while walking, potentially related to difficulties in coupling the coordination of postural control and gait [2,27,28].

Several limitations should be noted: i) we could not calculate a cognitive DT cost due to focusing the analysis only on the first turn, ii) the type of dual task was designed to be different for the turning tasks, but it could have introduced a bias in the results, iii) we did not measure cognitive abilities which may have contributed to turning difficulties, and iv) the lack of walking prior to the 360° turning in place could contribute to our results.

In summary, we confirmed with quantitative measures that turning in place is further compromised compared to turning while walking in people with PD who experience FoG compared to people who do not experience FoG, even in the absence of FoG episodes. We also showed that turning 360° in place seemed to require further cognitive effort compared to turning 180° while walking in people with FoG. Therefore, our findings may suggest that the increased cognitive and biomechanical demands of turning in place compared to turning while walking may explain the increased likelihood of freezing during turning in place.

CRediT authorship contribution statement

Matilde Bertoli: Methodology, Software, Formal analysis, Writing - original draft. **Ugo Della Croce:** Conceptualization, Writing - review & editing. **Andrea Cereatti:** Conceptualization, Writing - review & editing. **Martina Mancini:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgements

The authors are grateful to the participants in this study for their time, and Graham Harker for helping in data collection. This work was supported by grants from National Institute of Health via Career Development Award K99 HD078492 0IAI (Mancini PI) and 5R00 HD078492 (Mancini PI).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2019.09.001.

References

[1] J. Jankovic, Parkinson's disease: clinical features and diagnosis, J. Neurol. Neurosurg. Psychiatry 79 (2008) 368–376, https://doi.org/10.1136/jnnp.2007.131045.
[2] J.G. Nutt, B.R. Bloem, N. Giladi, M. Hallett, F.B. Horak, A. Nieuwboer, Freezing of gait : moving forward on a mysterious clinical phenomenon, Lancet Neurol. 10 (2011) 734–744, https://doi.org/10.1016/S1474-4422(11)70143-0.
[3] N. Giladi, A. Nieuwboer, Understanding and treating freezing of gait in parkinsonism, proposed working definition, and setting the stage, Mov. Disord. 23 (2008) S423–S425, https://doi.org/10.1002/mds.21927.
[4] A.H. Snijders, C.A. Haaxma, Y.J. Hagen, M. Munneke, B.R. Bloem, Freezer or non-freezer: clinical assessment of freezing of gait, Parkinsonism Relat. Disord. 18 (2012) 149–154, https://doi.org/10.1016/j.parkreldis.2011.09.006.
[5] M.E. Morris, F. Huxham, J. McGinley, K. Dodd, R. Iansek, The biomechanics and motor control of gait in Parkinson disease, Clin. Biomech. 16 (2001) 459–470, https://doi.org/10.1016/S0268-0033(01)00035-3.
[6] A.C. de Souza Fortaleza, M. Mancini, P. Carlson-Kuhta, L.A. King, J.G. Nutt, E.F. Chagas, I.F. Freitas, F.B. Horak, Dual task interference on postural sway, postural transitions and gait in people with Parkinson's disease and freezing of gait, Gait Posture 56 (2017) 76–81, https://doi.org/10.1016/j.gaitpost.2017.05.006.
[7] D.S. Peterson, L.A. King, R.G. Cohen, F.B. Horak, Cognitive contributions to freezing of gait in parkinson disease: implications for physical rehabilitation, Phys. Ther. 96 (2016) 659–670, https://doi.org/10.2522/ptj.20140603.
[8] J. Spildooren, S. Vercruysse, K. Desloovere, W. Vandenberghe, E. Kerckhofs, A. Nieuwboer, Freezing of gait in Parkinson's disease: the impact of dual-tasking and turning, Mov. Disord. 25 (2010) 2563–2570, https://doi.org/10.1002/mds.23327.
[9] G.M. Earhart, Dynamic control of posture across locomotor tasks, Mov. Disord. 28 (2013) 1501–1508, https://doi.org/10.1002/mds.25592.
[10] R. Camicioli, B.S. Oken, G. Sexton, J.A. Kaye, J.G. Nutt, Verbal fluency task affects gait in parkinson's disease with motor freezing, J. Geriatr. Psychiatry Neurol. 11 (1998) 181–185, https://doi.org/10.1177/089198879901100403.
[11] J.D. Schaafsma, Y. Balash, T. Gurevich, A.L. Bartels, J.M. Hausdorff, N. Giladi, Characterization of freezing of gait subtypes and the response of each to levodopa in Parkinson's disease, Eur. J. Neurol. 10 (2003) 391–398, https://doi.org/10.1046/j.1468-1331.2003.00611.x.
[12] H. Bhatt, F. Pieruccini-Faria, Q.J. Almeida, Dynamics of turning sharpness influences freezing of gait in Parkinson's disease, Parkinsonism Relat. Disord. 19 (2013) 181–185, https://doi.org/10.1016/j.parkreldis.2012.09.006.
[13] M. Mancini, K. Smulders, R.G. Cohen, F.B. Horak, N. Giladi, J.G. Nutt, The clinical significance of freezing while turning in Parkinson's disease, Neuroscience 343 (2017) 222–228, https://doi.org/10.1016/j.neuroscience.2016.11.045.
[14] J. Spildooren, C. Vinken, L. Van Baekel, A. Nieuwboer, Turning problems and freezing of gait in Parkinson's disease: a systematic review and meta-analysis, Disabil. Rehabil. 0 (2018) 1–11, https://doi.org/10.1080/09638288.2018.1483429.
[15] L.A. King, M. Mancini, K. Priest, A. Salarian, F. Rodrigues-De-Paula, F. Horak, Do clinical scales of balance reflect turning abnormalities in people with Parkinson's disease? J. Neurol. Phys. Ther. 36 (2012) 25–31, https://doi.org/10.1097/NPT.0b013e31824620d1.
[16] T. Herman, N. Giladi, J.M. Hausdorff, Properties of the "timed up and go" test: more than meets the eye, Gerontology 57 (2011) 203–210, https://doi.org/10.1159/000314963.
[17] A. Nieuwboer, L. Rochester, T. Herman, W. Vandenberghe, G.E. Emil, T. Thomaes, N. Giladi, Reliability of the new freezing of gait questionnaire: agreement between patients with Parkinson's disease and their carers, Gait Posture 30 (2009) 459–463, https://doi.org/10.1016/j.gaitpost.2009.07.108.
[18] C.G. Goetz, B.C. Tilley, S.R. Shaftman, G.T. Stebbins, S. Fahn, P. Martinez-Martin, W. Poewe, C. Sampaio, M.B. Stern, R. Dodel, B. Dubois, R. Holloway, J. Jankovic, J. Kulisevsky, A.E. Lang, A. Lees, S. Leurgans, P.A. LeWitt, D. Nyenhuis, C.W. Olanow, O. Rascol, A. Schrag, J.A. Teresi, J.J. van Hilten, N. LaPelle, P. Agarwal, S. Athar, Y. Bordelan, H.M. Bronte-Stewart, R. Camicioli, K. Chou, W. Cole, A. Dalvi, H. Delgado, A. Diamond, J.P. Dick, J. Duda, R.J. Elble, C. Evans, V.G. Evidente, H.H. Fernandez, S. Fox, J.H. Friedman, R.D. Fross, D. Gallagher, C.G. Goetz, D. Hall, N. Hermanowicz, V. Hinson, S. Horn, H. Hurtig, U.J. Kang, G. Kleiner-Fisman, O. Klepitskaya, K. Kompoliti, E.C. Lai, M.L. Leehey, I. Leroi, K.E. Lyons, T. McClain, S.W. Metzer, J. Miyasaki, J.C. Morgan, M. Nance, J. Nemeth, R. Pahwa, S.A. Parashos, J.S.J.S. Schneider, A. Schrag, K. Sethi, L.M. Shulman, A. Siderowf, M. Silverdale, T. Simuni, M. Stacy, M.B. Stern, R.M. Stewart, K. Sullivan, D.M. Swope, P.M. Wadia, R.W. Walker, R. Walker, W.J. Weiner, J. Wiener, J. Wilkinson, J.M. Wojcieszek, S. Wolfrath, F. Wooten, A. Wu, T.A. Zesiewicz, R.M. Zweig, Movement disorder society-sponsored revision of the unified parkinson's disease rating scale (MDS-UPDRS): scale presentation and clinimetric testing results, Mov. Disord. 23 (2008) 2129–2170, https://doi.org/10.1002/mds.22340.
[19] G.T. Stebbins, C.G. Goetz, D.J. Burn, J. Jankovic, T.K. Khoo, B.C. Tilley, How to identify tremor dominant and postural instability/gait difficulty groups with the movement disorder society unified Parkinson's disease rating scale: comparison with the unified Parkinson's disease rating scale, Mov. Disord. 28 (2013) 668–670, https://doi.org/10.1002/mds.25383.
[20] Z.S. Nasreddine, N.A. Phillips, V. Bedirian, S. Charbonneau, V. Whitehead, I. Collin, J.L. Cummings, H. Chertkow, The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment, J. Am. Geriatr. Soc. 53 (2005) 695–699, https://doi.org/10.1111/j.1532-5415.2005.53221.x.
[21] M. Bertoli, A. Cereatti, U. Della Croce, M. Mancini, U. Della Croce, M. Mancini, An objective assessment to investigate the impact of turning angle on freezing of gait in parkinson's disease, 2017 IEEE Biomed. Circuits Syst. Conf. BioCAS 2017 - Proc. IEEE, 2017, pp. 1–4, , https://doi.org/10.1109/BIOCAS.2017.8325122.
[22] M. El-Gohary, S. Pearson, J. McNames, M. Mancini, F. Horak, S. Mellone, L. Chiari, Continuous monitoring of turning in patients with movement disability, Sensors 14 (2013) 356–369, https://doi.org/10.3390/s140100356.
[23] M. Bertoli, A. Cereatti, D. Trojaniello, et al., Estimation of spatio-temporal parameters of gait from magneto-inertial measurement units: multicenter validation among Parkinson, mildly cognitively impaired and healthy older adults, Biomed. Eng. (2018), https://doi.org/10.1186/s12938-018-0488-2 Online.
[24] J.D. Schaafsma, Y. Balash, T. Gurevich, A.L. Bartels, J.M. Hausdorff, N. Giladi, Characterization of freezing of gait subtypes and the response of each to levodopa in Parkinson's disease, Eur. J. Neurol. (2003), https://doi.org/10.1046/j.1468-1331.2003.00611.x.
[25] M. Mancini, A. Weiss, T. Herman, J.M. Hausdorff, Turn around freezing: community-living turning behavior in people with Parkinson's disease, Front. Neurol. 9 (2018) 1–9, https://doi.org/10.3389/fneur.2018.00018.
[26] A. Bengevoord, G. Vervoort, J. Spildooren, E. Heremans, W. Vandenberghe, B.R. Bloem, A. Nieuwboer, Center of mass trajectories during turning in patients with Parkinson' s disease with and without freezing of gait, Gait Posture 43 (2016) 54–59.
[27] E.M.J. Bekkers, B.W. Dijkstra, K. Dockx, E. Heremans, S.M.P. Verschueren, A. Nieuwboer, Clinical balance scales indicate worse postural control in people with Parkinson's disease who exhibit freezing of gait compared to those who do not: a meta-analysis, Gait Posture 56 (2017) 134–140, https://doi.org/10.1016/j.gaitpost.2017.05.009.
[28] C. Schlenstedt, M. Mancini, J. Nutt, A.P. Hiller, W. Maetzler, G. Deuschl, F. Horak, Are hypometric anticipatory postural adjustments contributing to freezing of gait in Parkinson's disease? Front. Aging Neurosci. 10 (2018) 1–9, https://doi.org/10.3389/fnagi.2018.00036.