An Objective Assessment to Investigate the Impact of Turning Angle on Freezing of Gait in Parkinson's Disease

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Abstract—**Freezing of gait (FoG) is often described in subjects with Parkinson's disease (PD) as a sudden inability to continue the forward walking progression. FoG occurs most often during turning, especially at sharp angles. Here, we investigated 180 and 360 degrees turns in two groups: PD subjects reporting FoG (FoG+), and PD subjects without FoG (FoG-). Forty-three subjects (25 FoG+, 18 FoG-) wore an inertial sensor on their back while walking back and forth continuously for 2 min (reversing direction with a 180° turn), and while turning in place for 1 min (alternating 360° turning in opposite directions). Objective measures (turn duration, peak velocity, jerkiness and range of acceleration) were computed during the turns and compared across FoG+ and FoG- groups. Results showed that FoG+ compared to FoG- took significantly a longer time to complete 360° turns than 180° turns. A significant lower turn peak velocity, higher jerkiness and an increased range of medio-lateral acceleration was also found in FoG+. Significant differences between the two groups across the two turning tasks validated the hypothesis that sharper turns might cause higher instability in FoG+ compared to FoG-.**

Keywords—PD, FoG, turn, inertial sensor

I. INTRODUCTION

Freezing of gait (FoG) is one of the most disabling features in Parkinson's Disease (PD). It is associated with increased risk of falls, it interferes with daily activities and it substantially affects quality of life [1]. FoG denotes the "absence or marked reduction of the forward progression of the feet, despite the intention to walk" [2]. FoG is an episodic phenomenon of still controversial pathophysiology. However, FoG episodes are usually triggered by postural transitions, such as step initiation or turning, or by environmental constraints, such as passing through a narrow path or being under time pressure [3], [4]. Specifically, it has been shown that turning may be the most effective task in provoking FoG [5]. In fact, turning is a challenging motor task, requiring a coupling between anticipatory postural adjustments and scaling of walking [2].

Generally, subjects with PD walk slowly with short stride length, even more so prior to and during a change in walking direction. Subjects with PD experiencing FoG (freezers) during 180° turns exhibit a different motor strategy compared to healthy controls and non freezers (reduced step width, reduced medial deviation and increased forward progression of the center of mass) [6]. In addition, it has been observed that subjects with PD display greater variability at sharper turns (i.e turning at larger angle), and sharper turns tend to particularly elicit freezing episodes [7], [8]. Snijders et al., and Mancini et al., showed that repeated 360° turns on the spot were more effective in provoking FoG compared to 180° turns during walking [5], [9]. 360° turn is indeed a task demanding a fine postural control tuning, and it has been hypothesized that FoG may be related to a lack of initiation of postural adjustments [10]. Moreover, in a stepping in place task FoG was associated with rapid, small and inefficient weight transfers, possibly due to mismatched gains in the perception and execution of the movement [11].

Recently, wearable sensors have increasingly been used for instrumented clinical evaluations to obtain quantitative outcomes. Small inexpensive inertial sensors are becoming a powerful tool to perform motion analysis due to their ease of use. Instrumented motor tests are nowadays widely accepted [12]. In particular, the assessment of turning with inertial sensors allows investigating complex locomotor patterns and gathering additional insights on motor control [13].

Several studies ([6], [7], [9], [14], [15]) demonstrated that objective measures from a turning task can differentiate between PD patients and healthy controls, and highlighted the need for further research to focus on the clinical relevance of such measures. In particular, as also suggested in Visser et al., it would be interesting to correlate yaw angular velocity during turning to clinical measures as those for FoG, as this approach might be useful to evaluate the outcome of intervention studies aimed at improving FoG [14]. Furthermore, investigating the underlying mechanism of FoG is important to advice an effective rehabilitation intervention.

To this purpose, we developed and applied a method, based on the use of a single inertial sensor on the lower trunk, to perform a quantitative gait analysis in presence of 180° and 360° turns in freezers and non freezers PD populations (FoG+ and FoG-).

II. MATERIAL AND METHODS

A. Participants

Forty-three subjects with PD were recruited through the Parkinson's Center of Oregon clinic at Oregon Health & Science University (OHSU). All gave informed, written consent to a protocol approved by OHSU's Institutional Review Board. Individuals were excluded if they could not walk seven meters without walking aids, or if they had any neurological disease (other than PD), musculoskeletal or vestibular disorder, and dementia.

Subjects were divided in two groups based on their answer to the first question of the New FoG Questionnaire (NFOG-Q): "Have you experienced FoG in the past month?". Twenty-five (19M, 6F) answered 'yes' and were classified as freezers (FoG+), and eighteen (14M, 4F) were assigned to the FoG- group. FoG+ mean age was 69±7 years, and disease severity was rated 45.7±12 as per the motor section of the Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS-III). FoG- mean age was 70±7 years, and mean MDS-UPDRS-III score was 43.6±12.

B. Experimental Setup

Testing was carried out in the practically defined OFF state (12+ hours of PD medication withdrawal). At the beginning of the testing session, a trained examiner administered the motor section of the MDS-UPDRS to quantify disease severity and the NFOG-Q to assess the perceived severity of FoG.

An inertial sensor (Opal - APDM, Inc) was positioned on the back approximately at the level of L5. Subjects then performed two motor tasks: 180° and 360° turns. The 180° turns were part of a two minutes long walk, where the subject walks straight for 7 meters at a comfortable speed, turns back and keep walking in the opposite direction. No indications were given about direction of turning or strategy. For the 360° turns, the subject turned in place, starting from a standing position, 360° clockwise, and then 360° counter-clockwise, repeating this sequence for one minute.

The reference frame of the inertial sensor was oriented approximately along the three human body anatomical directions. An estimate of its orientation with respect to the global frame was provided by an on-board Kalman filter. The signals from the Opal sensor were recorded at 128 Hz, streamed wirelessly to a laptop and stored for subsequent offline analysis with Matlab (MathWorks. R2016a).

C. Data Analysis

Inertial sensor data were automatically segmented to detect turns. To this purpose, two different algorithms were implemented to identify the 180° and 360° turns.

For the 180° turns, the algorithm was based on previous work from [16]. The angular velocity was expressed in the global coordinate system and its vertical component low pass filtered (Butterworth, 1.5 Hz cutoff frequency). The offset was then removed (by subtracting the mean of the signal during the first 3 seconds, during which the subject was standing still). Candidate turns were detected as vertical angular velocity peaks higher than 15°/s, and for each peak the preceding and following 5°/s threshold crossing were set as instants of turn beginning and ending. Additional checks were performed on the candidate turns in order to isolate the 180° turn. First of all, turns in the same direction separated by less than 0.1s were merged. Then, turns lasting less than 0.5s or more than 10s were discarded. Finally, the relative turn angle was computed integrating the vertical angular velocity over the turn duration and, when resulting less than 45°, lead to the turn elimination.

For the 360° turns, a novel algorithm was implemented based on an approach exploiting local magnetic field inversion and angular velocity [17]. The two planar components (AP and ML) of the magnetometer signals were low pass filtered (Butterworth, 1 Hz cutoff frequency), and their sum was computed. The mean value computed during the first 3 s from this composed signal was removed, and a moving average (windows length 0.5 s) was used for smoothing. Prototype turns were detected as peaks higher than 70% of the signal max value and further apart than 3s, and for each peak the preceding and following 20% threshold crossing were used to isolate the turn. For each prototype turn, the zero-crossings of the filtered, offset-free vertical angular velocity were used as turn beginning and ending instants. An additional control was performed in case of an incorrect merging of two consecutive turns: the turning angle was computed integrating the vertical angular velocity absolute value over the turn duration and, when resulting greater than 400°, lead to the turn division.

For each detected turn (for both trials, see example in Fig. 1), the following objective measures were computed: turn duration, peak angular velocity, jerkiness and range of acceleration. Specifically, turn duration (s) was measured as the interval of time from the beginning to the ending of the turn.
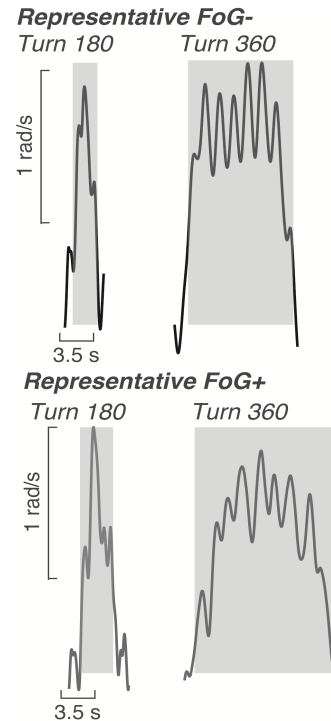

Fig. 1. Time series of trunk angular velocity profiles during the 180 and 360 turning tasks in a FoG- (upper panel) and a FoG+ (lower panel). In FoG+ the time needed to complete the turns is longer than in FoG-.

Turn peak velocity (°/s) was defined as the vertical angular velocity maximum peak amplitude. Turn jerk (g^2/s), time derivative of acceleration, was used to quantify fluidity of turning in both antero-posterior (AP) and medio-lateral (ML) directions. Turn range (m/s^2) was also computed for both ML and AP accelerations. At first the metrics where averaged grouping them by turning direction (most affected side vs. least affected side), but since there was no evident difference and their distribution was overlapping, the average between sides for each subject was used for the statistical analysis. A two-way (groups×task) repeated measures analysis of variance (ANOVA) was used to investigate the difference in the metrics between groups (FoG+/FoG-) and within tasks (180°/360°). Since turn jerk and turn duration distributions were not normal, for the ANOVA analysis they were transformed in logarithmic scale. SPSS (IBM V.23) was used to run statistical analyses.

III. RESULTS

Table I summarizes the mean (STD) of each turn measure across groups and the ANOVA results, significant differences ($p<0.05$) are indicated in bold.

A significant group, task, and group x task interaction effect was observed for turn duration and both AP- and ML- jerks. Turn duration was longer in the 360° task compared to the 180° task in both groups (significant task effect, F=173.09, p<0.001), Fig. 2. In addition, FoG+ took a longer time to complete the turn compared to FoG- both during the 180° (2.68s FoG- ; 3.40s FoG+) and the 360° task (5.59s FoG-; 9.42s FoG+), with a significant group by task effect (F=6.99, p=0.01). AP- and ML- jerks were significantly higher in the 360° task compared to the 180 task (F=30.42, p<0.001; and F=70.59, p<0.001, respectively) with FoG+ showing a significantly higher increase in turn jerk during the 360° task compared to 180° (significant interaction effect, AP: F= 6.18, p=0.02; ML: F= 9.36, p<0.001).

A significant group effect was found for turn peak velocity, which was lower in FoG+ (F= 15.86, p<0.001), and there was a significant trend (F= 5.09, p=0.03) towards lower peak velocity during 360° task within FoG+ (mean peak velocity remains almost constant in FoG- in 180° and 360° task, while it decreases in FoG+). No significant task effect was observed for turn peak velocity.

Neither AP- nor ML- ranges were significantly different across groups. For AP-Range there was a significant task effect (greater AP-Range for the 180° task), but no group by condition effects. Instead, ML-range showed a significant task and interaction effect (greater ML-range during 360° compared to 180° within FoG+).

IV. DISCUSSION

The aim of this study was to quantitatively characterize 180° and 360° turns in subjects with PD to investigate the impact of turning angle on FoG.

The FoG+ group took longer time to complete turns, performing them at slower speed, with greater jerkiness, but similar range of acceleration. Every metric, except turn peak velocity, showed a significant task effect, indicating a difference in the 360° turn compared to the 180° turn. The significant interaction effects, in all the turning metrics but AP-range, supports the hypothesis that the FoG+ group showed different turning behaviors depending on the turning task.

Specifically, the increase in turning duration from 180° to 360° was larger in the FoG+ group. This result is consistent with [8], in which the FoG+ group was found to walk more slowly than healthy controls and FoG- during a 180° turn, and even more so in the 360° turn. A potential explanation for such increase is that FoG+ showed freezing episodes in the 360° task but not in the 180° task, leading to an increase in turning duration.

A similar pattern was observed for ML- and AP- jerks. In fact, the increase in AP- and ML- jerks from 180° to 360° turn was larger in the FoG+ group. This difference in turning smoothness could be the result of a larger number of steps needed to complete a turn in the FoG+ group, or of more FoG episodes. Further analysis will investigate the association between the amount of freezing and the metrics presented here.

The turn peak velocity was similar among turning tasks, but interestingly, the FoG+ group tended to slow down during the 360° turn compared to the 180° while FoG- showed a similar turn peak velocity in both turn tasks. This is therefore suggesting that the FoG+ subjects have more difficulties in completing the 360° turn compared to the 180° turn. This finding is in accordance with our previous results characterizing the 360° turn, where the FoG+ group showed a lower peak speed than the FoG- (and healthy controls).

TABLE I.   SUMMARY OF THE OBJECTIVE MEASURES IN SUBJECTS WITH (FOG+) AND WITHOUT (FOG-) FREEZING OF GAIT.

| Measure	Group	180° mean (STD)	360° mean (STD)		Group	Task	Interaction
duration (s)	*FoG-*	2.68 (0.54)	5.59 (4.09)	F-value	*16.93*	*173.09*	*6.99*
	FoG+	3.40 (0.72)	9.42 (4.36)	p-value	*0.00*	*0.00*	*0.01*
peak velocity (°/s)	*FoG-*	131.48 (31.11)	133.22 (39.21)	F-value	*15.86*	2.81	*5.09*
	FoG+	104.51 (19.82)	92.73 (26.82)	p-value	*0.00*	0.10	*0.03*
ML-jerk (g^2/s)	*FoG-*	0.080 (0.02)	0.106 (0.03)	F-value	*8.02*	*70.59*	*9.36*
	FoG+	0.092 (0.03)	0.174 (0.09)	p-value	*0.01*	*0.00*	*0.00*
AP-jerk (g^2/s)	*FoG-*	0.065 (0.02)	0.077 (0.03)	F-value	*7.00*	*30.42*	*6.18*
	FoG+	0.076 (0.03)	0.116 (0.05)	p-value	*0.01*	*0.00*	*0.02*
ML-range (g)	*FoG-*	0.40 (0.08)	0.40 (0.11)	F-value	0.25	*4.48*	*4.81*
	FoG+	0.38 (0.08)	0.44 (0.013)	p-value	0.62	*0.04*	*0.03*
AP-range (g)	*FoG-*	0.32 (0.07)	0.28 (0.08)	F-value	0.59	*14.24*	0.61
	FoG+	0.30 (0.07)	0.27 (0.05)	p-value	0.45	*0.00*	0.44
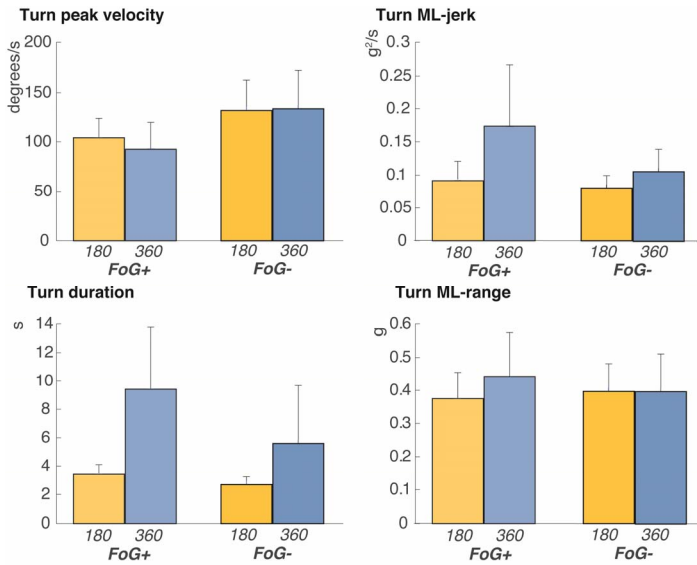
Fig. 2. Mean and SEM of the objective measures. The greatest chages can be observed in the FoG+ during the 360° turn (decrease in velocity, and increase in ML-jerk, ML-range and duration).

The ML-range of acceleration during turn showed a task and a group x task interaction effect, suggesting that only FoG+ have a greater ML acceleration in the 360° turn compared to the 180° turn. Interestingly, few studies ([6], [11]) showed either a greater ML center of mass displacement in FoG+ compared to FoG-, or a reduced ML weight shifting during a repetitive stepping in place task. Our results did not show significant differences between the two groups for ML-range of acceleration, however we did not analyze separately turns with and without FoG episodes.

AP-range did not show an interaction effect, but it showed a strong task effect (p<0.001). The intrinsic motor task characteristics, walking and turning versus turning in place, could explain such difference. In fact, in the 180° task the subjects are progressing forward before the turn, instead for the 360° task subjects are more prone to shift their weight laterally to complete the task. This difference in the experimental set-up in measuring 180° and 360° turn is also a limitation of the present study.

Nonetheless, our previous assertions do not lose their validity. Our findings support the hypothesis that turning at a sharper angle may pose more difficulties for FoG+, possibly due to an increasing demand on bilateral coordination [8].

These results can be useful to develop algorithms for generating a biofeedback aimed at alleviating or preventing FoG prior challenging motor tasks. The findings here reported can be also relevant for the outcome evaluation after interventions aimed at reducing FoG episodes, or to devise optimal and more effective rehabilitation treatments. The preliminary results reported in the present study suggest that the analysis of walking test including 360° turn using a single inertial sensor is a promising solution for analyzing FoG mechanism in PD population.

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