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The Transition from Standing to Walking Is Affected in People with Parkinson's Disease and Freezing of Gait

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Abstract

Background: It has been hypothesized that freezing of gait (FOG) in people with Parkinson's disease (PD) is due to abnormal coupling between posture and gait.

Objective: In this study, we examined the relationship between anticipatory postural adjustments (APAs) preceding gait initiation and the kinematics of the first two steps between people with FOG and without FOG.

Methods: The kinetics and kinematics of self-initiated gait were recorded in 25 people with PD (11 with FOG, 14 without FOG). Outcome variables included the amplitude and timing of the ground reaction forces (GRFs), center of pressure (CoP) shifts and the spatial and temporal characteristics of the first and second steps.

Results: The magnitude and timing of the APA phase of gait initiation were not significantly different between participants with and without FOG, yet the first step in the FOG group was distinguished by a significantly wider and less variable first step width, followed by a subsequent wider and shortened second step with reduced toe clearance. Multiple linear regression showed that the relationship between the initial conditions (stance width), APAs (posterior shift of the CoP) and the kinematics of the first step were different between groups with a significantly increased slope in the FOG group.

Conclusion: These findings demonstrate that the transition from standing to walking is different between those with and without FOG and that alterations in the initial conditions or APAs are more likely to impact the execution of the two steps in people with FOG.

Keywords

Gait initiation; Parkinson's disease; anticipatory postural adjustments; stepping

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to report.

INTRODUCTION

Parkinson's disease (PD) is a progressive neurological disease that often results in debilitating impairments in postural stability and gait, including the phenomenon of freezing of gait (FOG). FOG is an episodic disturbance in motor control characterized by a brief "absence or marked reduction of forward progression of the feet despite the intention to walk" [1, 2]. Currently, the pathogenesis of FOG is poorly understood. While the incidence and duration of FOG episodes can often be reduced with oral dopamine replacement therapy (levodopa) [3] or deep brain stimulation [4, 5], efficacy usually diminishes as the disease progresses [6]. The presence and severity of FOG is associated with an increased risk of falls, hospitalization, and increased morbidity [7–10].

A characteristic feature of FOG is that episodes are frequently triggered during transitions in motor behavior [1, 11]. Examples of transitions that can evoke freezing are the initiation of gait from a quiet standing position, turning, changing speed when approaching a narrowed hallway or doorway, or alterations in trajectory to avoid an obstacle. Transitions in movement are preceded and accompanied by anticipatory postural adjustments (APAs) that accelerate the center of mass towards the support leg to maintain dynamic equilibrium in anticipation of the destabilizing forces generated by the intended step [12, 13]. Accordingly, it has been proposed that FOG may be caused by abnormal function in neural circuits that mediate the coupling of postural adjustments with locomotion [1, 14]. These circuits may be differentially influenced by a variety of systems, including motor (asymmetry), cognitive (attentional set-shifting) and/or affective (anxiety) factors, that result in the expression of different FOG phenotypes [15].

APAs are generated prior to the initiation of forward stepping in order to accelerate the body center of mass forward and laterally toward the initial stance leg prior to the execution of the first step [16]. During gait initiation, APAs are characterized by loading and unloading of the initial step and stance legs respectively and a shift in the center of pressure backward and laterally toward the step leg [17]. In healthy participants, the position and momentum of the center of mass of the body at the time of toe-off, which are controlled by the APA, predict the first step, but not the second step placement [18]; although these steps can be controlled by mid-course adjustments when necessary (e.g., a sudden change in location of a stepping target) [16, 19]. A variety of studies have shown that APAs are attenuated and prolonged, or absent, in people with PD when off medication, particularly when movement is initiated in the absence of an external sensory cue (self-initiated) [20, 21]. Additionally, recent studies have shown that the impairment in APA generation in people with FOG is comparable to those without FOG [21–24]. Moreover, differences between people with and without FOG appear to occur late in the step execution phases or during the first and second steps [22, 24–27]. It is thus possible that those with FOG have an additional deficit during the step execution that affects their first two steps. Taken together, these findings suggest that disturbances in the generation of APAs generally seen in people with PD may impact the execution of the first and second steps differently between those with and without FOG.

The purpose of this study was to evaluate how freezing affects the transition from standing to walking by examining the relationship between APAs and the initiation of the gait cycle

in people with PD with and without FOG. We hypothesized that the execution of the first two steps would be highly dependent upon the magnitude and timing of the APA in the participants without FOG, while the first two steps in the FOG group would be independent of the APA.

METHODS

Participants and tasks

Twenty-five people with a diagnosis of PD (11 FOG, 14 nFOG) were recruited to the Movement Disorders Lab at the University of Minnesota. Participants were excluded if they had a history of cardiovascular, pulmonary, musculoskeletal, metabolic, or neurological disorder besides PD, or were unable to walk independently for 50 m. Participants were tested in the practically defined off-medication state after overnight withdrawal from all Parkinson's medications (12 or more hours after their last dose). Each participant completed the Montreal Cognitive Assessment (MOCA) [28], the New Freezing-of-Gait Questionnaire (FOG-Q) [29], and the Unified Parkinson's Disease Rating Scale Motor Subsection (UPDRS-III) [30]. The presence of FOG was classified based on the individual's response to question 1 of the FOG-Q and direct observation of a FOG episode during a clinical or laboratory visit. If the presence of FOG was in doubt, the participant was asked to turn in place multiple times to the right and left. This turn test has been shown to be an effective and reliable method to evoke freezing [31]. In addition, medical records were consulted for a reported history of FOG. Participants gave written informed consent and the University of Minnesota Institutional Review Board approved all procedures.

Participants performed a self-initiated gait task [21]. The task began with the participant standing on a walkway with their feet placed at their self-chosen stance width (this was kept consistent across trials). After a period of steady-state standing, the researcher said the word "anytime" and participants were instructed to wait at least 3–5 seconds then initiate forward walking "as quickly as possible" starting with their preferred stepping foot (also kept consistent across trials). Participants took at least 4 steps toward the end of the walkway before stopping. A total of 12 trials were performed (except for 1 participant who performed 10 trials in order to lessen fatigue).

Force plates (Kistler, Amherst, NY) beneath each foot were used to measure the ground reaction forces (GRFs) and moments in the 3 principal axes and were collected at a sampling rate of 1000 Hz. Kinematics of the steps were recorded using an 8-camera motion capture system at 120 Hz (Simi Reality Motion Systems, Munich, Germany). Foot trajectories were modelled using markers placed on the back-center of each heel, medial and lateral malleoli, and base of the 2nd metatarsal. Participants wore a safety harness, belayed to the ceiling, as a safety measure in case of a fall.

This study is a secondary analysis of data presented, in part, in Lu et al. (2017) [21]. A subset of the trials (self-initiated condition only) was used for analysis here. All trials with cues were omitted in order to focus on any potential changes in self-initiation of gait even when a freezing or festination event did not occur. All of the participants with PD and FOG

demonstrated clear FOG during their visit, but there were no trials of self-initiated gait where a participant froze during the data collection.

Outcome variables

The outcome measures were derived from the vertical ground reaction forces (GRFv), the net center pressure shifts in the medial-lateral (CoPml) and anterior-posterior (CoPap) directions, and the kinematics of the heel and toe markers for the first two steps (for methods see Lu et al., 2017 [21]) (Fig. 1). GRFs and CoP data were digitally filtered with a 2nd order low-pass Butterworth filter with a cutoff frequency of 40 Hz [32]. Kinematic data were filtered with a 2nd order low-pass Butterworth filter at 10 Hz.

Kinetic and kinematic variables were manually marked by a rater blinded to the group assignment using a custom MATLAB (Mathworks, Natick, MA, USA) program and reviewed by two other investigators. The variables that were measured from the kinetics were: the onset time of the initial weight shift (APA onset, defined as the time when the vertical force visually deviated from baseline values), local maximum loading and local minimum unloading GRFv's under the step and stance legs respectively, local maximum initial displacement of the CoP posteriorly (CoPap1) and laterally (CoPml) toward the stepping foot, the time when step unloading and stance leg loading began (termed the transition point, where the GRFv's re-cross their baseline values), the second local minimum posterior peak of the CoP that typically occurs near the time of step leg toe-off (CoPap2), and the time of first and second step toe-off (measured from weight shift onset). The incidence of trials during which the APA phase was absent was recorded. If an APA phase was absent, the peak amplitudes were set to zero, and the transition point was set equal to the weight shift onset (defined as the onset of step foot force unloading) (See also [21,33]). From the kinematics, the first step length and width were defined as the difference (in the A-P and M-L directions respectively) between the right and left heel markers at the end of the first and second steps. The step durations were calculated from toe-off to heel contact and used to calculate the average step speed. Step clearance was defined as the vertical displacement of the toe marker from the floor at the point of maximum velocity during mid-swing.

Statistical analysis

All outcome variables were calculated as the mean and coefficient of variation (CV) across trials for each participant. Group differences in the outcome variables and demographics were investigated using one-way ANOVAs. The relationships between initial conditions or APAs variables and the execution of the first and second steps were tested using Pearson's linear correlations (two-tailed). Differences in correlations between groups were tested by centering the independent variables (to reduce collinearity) and conducting a multiple linear regression with group as an interaction term. The level of significance was set to $p < 0.05$. Multiple linear regressions were chosen for the conservative nature of declaring significance in the interaction term. In order to decrease the potential of a Type I error, correlations were restricted to variables logically connected to one another (e.g., M-L APA components to step widths and A-P APA components to step lengths).

RESULTS

Demographics

There was no significant difference between groups in age (FOG: 66 ± 11 years; nFOG: 64 ± 9 years; $p = 0.607$), height (FOG: 173 ± 10 cm; nFOG: 170 ± 7 cm; $p = 0.396$), weight (FOG: 76 ± 12 kg; nFOG: 74 ± 12 kg; $p = 0.643$), MOCA score (FOG: (FOG: 25 ± 2; nFOG: 27 ± 3; $p = 0.176$), or off-medications UPDRS-III score (FOG: 31 ± 8; nFOG: 29 ± 11; $p = 0.675$). Compared to the nFOG group, the FOG group had a significantly longer disease duration (FOG: 8 ± 4 years; nFOG: 5 ± 4 years; $p = 0.047$) and a higher levodopa equivalent daily dosage (FOG: 1060 ± 396 mg; nFOG: 581 ± 434 mg; $p = 0.009$). The off-medications Hoehn and Yahr scores for the FOG group were 3 ± 0.5, and 2.5 ± 0.5 for the nFOG group [34].

Group differences across gait initiation phases

No significant differences were observed between groups in the initial stance width or the timing and peak amplitudes of the APA variables (Table 1). In addition, there were no group differences in the mean anterior-posterior or medial-lateral CoP locations relative to the estimated ankle joint center of rotation in the baseline period prior to APA onset (i.e., the initial lean of the center of mass was similar between groups). The first step of gait initiation in the FOG group was significantly wider ($p = 0.018$) and had a lower step width CV ($p = 0.039$) compared to the nFOG group (Fig. 2). The length of the first step was also shorter in the FOG group by an average of 18%, but this difference did not reach significance ($p = 0.064$). The second step in the FOG group was significantly shorter ($p = 0.043$) and wider ($p = 0.026$). Step height during mid-swing was not significantly different between groups during the first step ($p = 0.161$), but was significantly lower in the FOG group during the second step ($p = 0.017$).

Relationships between initial conditions, APAs and execution phases of gait initiation

Behavioral differences between groups in the execution of the first step were investigated further by examining relationships between the initial conditions (stance width) or APA variables and the first step kinematics. First step width was significantly correlated with initial stance width in the FOG ($r^2 = 0.776$, $p < 0.001$), but not the nFOG group ($r^2 = 0.008$, $p = 0.767$) (Fig. 3A). Multiple linear regression with group x initial stance width as an interaction factor showed that the slope of the correlation between step width and stance width was significantly higher in the FOG group ($p = 0.037$), suggesting that step width may change with the initial stance width in the FOG group (77.6%), but not the nFOG group (0.8%). Step width was also significantly correlated with the peak lateral excursion of the CoP during the APA in the FOG ($r^2 = 0.494$, $p = 0.016$), but not the nFOG ($r^2 = 0.055$, $p = 0.418$) group, however, the group x CoPml interaction was not significant ($p = 0.069$) (Fig. 3B). Since our data showed that step width was correlated to both stance width and CoP lateral shift in the FOG group, we investigated the possibility of using stance width as a covariate in our multiple linear regression of step width and CoP lateral shift. However, we found that the correlation between initial stance width and CoP lateral peak was relatively high ($r^2 = 0.34$, $p = 0.002$), which violates the assumption that the predictor and the covariate should be independent of each other. Therefore, the covariate analysis would not

be able to give valid results about each predictor due to multicollinearity. Nevertheless, wider initial stances are likely linked to both larger lateral CoP lateral peaks [35] and wider first steps in our cohort.

In both PD cohorts, the peak amplitude of the first posterior excursion of the CoP correlated with first step length (nFOG: $r^2 = 0.319$, $p = 0.035$, FOG: $r^2 = 0.520$, $p = 0.012$) (Fig. 3C). The slope of the correlation of the posterior CoP shift to step length was significantly greater in the FOG compared with the nFOG group as shown by a significant group × CoPap1 interaction ($p = 0.036$). Step length was also significantly correlated with the second peak of the CoP shift (near toe-off) in both the FOG ($r^2 = 0.229$, $p = 0.012$) and the nFOG groups ($r^2 = 0.623$, $p < 0.001$) but the slopes of the regressions were not significantly different between groups (group × CoPap2 interaction, $p = 0.351$) (Fig. 3D).

DISCUSSION

The results of this study demonstrate that, despite generally similar initial conditions and similar APA profiles, the execution of the first and second steps were different between individuals with and without FOG. It is worth noting that the inter-participant variability of initial stance widths was larger in the FOG group, but there were no differences in the initial CoP locations relative to the ankle prior to APA onset. In the participants with FOG, the first and second steps were characterized by shorter and wider steps, reduced toe clearance and less trial-to-trial variability. Although correlations with small sample sizes ($n = 11$ and 14) should be interpreted cautiously, the slopes of the correlations between the initial stance width, or posterior excursion of the CoP, and the execution of the first step were significantly greater in the FOG group, using a conservative multiple linear regression approach. This may suggest, contrary to our hypothesis, that the consequences of stance width changes or impairment in APA generation may affect the performance of gait initiation to a greater extent in people with FOG compared to those without FOG.

The primary difference between the FOG and nFOG groups was not in initial stance width, initial net CoP location, or the generation of the APA, but the execution of the first and second steps. Consistent with previous studies [22, 24–26], the length of the initial steps were significantly reduced in the FOG group. The first and second steps were on average of 18% and 20% shorter respectively in the FOG compared with the nFOG group. The first and second step widths were also wider and associated with reduced trial-to-trial variability in the FOG group. Overall, the first step was an average of 27% wider and 29% less variable and the second step was 35% wider and 32% less variable in the FOG group compared with the nFOG group. Short, rapid steps during walking have been shown to provoke episodes of FOG [25], leading to the sequence hypothesis that progressive shortening of steps can trigger FOG [36, 37]. Thus, it is conceivable that a markedly short first step during gait initiation could also trigger a freezing event. Yet, it is noteworthy that the first step length in both groups was considerably shorter than the distance reported in healthy adults [26, 38]. For example, Okada et al. (2011) [26] reported an average step length of approximately 84% of leg length (dashed line in Fig. 2) whereas the average first step length in the FOG and nFOG participants were 49.0% and 59.8% of leg length respectively. This raises the question of why a shortened step length might trigger freezing in some individuals, and not others.

A key finding of this study was that the differences in the first and second step execution between groups were preceded by APAs that were comparable in both magnitude and timing. We have previously reported that APA generation was not significantly different between the FOG and nFOG groups during both self-initiated and sensory cued conditions [21]. Similar findings were recently reported by Schlenstedt et al. (2018) [24] during self-initiated stepping, but differences between groups emerged when gait initiation was paired with a dual task. Significant attenuation of the posterior shift in the CoP near the time of toe-off (2nd peak of the CoP_{AP}) has been reported in people with FOG [22, 27], and this is consistent with the idea that differences between those with and without FOG emerge in the transition from the APA to the first step. Nonetheless, it is important to note that the APAs in both groups were markedly attenuated compared to data obtained in healthy older adults using a comparable self-initiated stepping protocol [39].

It has been postulated that FOG is caused by impaired coupling of posture with gait (Nutt et al., 2011). Accordingly, our *a priori* hypothesis was that the relationship between the APA and first step would be significantly reduced in the FOG compared with the nFOG group. This hypothesis was not supported by the findings of this experiment, in fact the opposite result was observed. In the group without FOG, the initial step width was not significantly correlated to either the initial stance width or peak lateral excursion of the CoP. In other words, initial stance width had less influence on the placement of the first step in the nFOG group than in the FOG group. The average initial stance width was 15.1 cm, followed by first and second step widths of 12.0 and 9.3 cm respectively (see Fig. 2). This progressive reduction in step width over the first two steps reflects the rapid transition from a wide base of support during standing to a relatively narrow stance width during steady-state gait [40]. This progression was less visible in the FOG group, as average initial stance width was 16.2 cm, followed by first and second step widths of 15.2 and 12.6 cm. Also in contrast with the nFOG group, in the FOG group, the width of the first step was tightly correlated to the initial stance width and lateral shift in the CoP. Wide initial stance widths were associated with a wide first step and narrow stance widths to a narrow first step. The initial stance width of the nFOG group was not significantly different from the FOG group, yet there was no significant correlation between initial stance width and first step width. The range of initial stance widths observed in the FOG group was nearly double the range in the nFOG group, which may have affected the strength of the correlations. In this experiment, participants were asked to adopt their natural and comfortable stance width prior to stepping and this position was held constant across trials. Future experiments could systemically vary the initial stance widths within-participants to further explore the influence on stepping, keeping in mind that forced alterations in quiet standing stance width may unnaturally alter APA and step dynamics.

The first step width was positively correlated with the lateral shift in the CoP in the FOG group, but not the nFOG group, although the correlations were not significantly different between groups ($p = 0.069$). Additionally, the fact that stance width was correlated to both CoP lateral shift and step width suggests that stance width may mediate step widths by modifiying the CoP lateral shift. Regardless, this positive correlation of the CoP lateral shift and step width is counterintuitive since the lateral shift in the CoP towards the stepping leg during the APA should function to accelerate the center of mass towards the initial stance

limb prior to toe-off and therefore large CoP excursions would be expected to be associated with a narrower step width. Yet, in the FOG group, first step widths remained abnormally wide despite relatively large lateral shifts in the CoP. Rocchi et al. [35] showed that wider initial stance widths were associated with larger lateral and posterior shifts in the CoP, a longer first step length and increased step velocity in healthy adults and people with PD. However, the capacity of the PD group to adapt to a widened initial stance width was significantly reduced, particularly in the off-medication state, compared with control participants. They hypothesized that a narrowed initial stance width may reflect a compensatory strategy due to a reduced ability to generate a sufficient shift in the CoP. In keeping with this idea, our data demonstrate that, in people with FOG, adoption of a wider stance width is correlated to an abnormally wide first step, despite a substantial lateral shift in the CoP, and possible overflow to a subsequently wide, shortened second step with reduced toe clearance. Muir et al. found that step width did not change with age, but age was associated with an increased step width variability. They hypothesized this to reflect more errors in foot placement and/or decreased center of mass control [40]. The FOG group in our study had decreased step width variability of their abnormally wide step, which may be a different symptom, but a similar loss of center of mass control. Those in our FOG group appear to modify their APA according to their self-selected stance width, but the first step width remains wide when it would be expected to be narrow.

In agreement with previous studies [35, 41], first step length was correlated with the peak amplitudes of the first and second peaks of the posterior excursion of the CoP (Fig. 3). However, the slope of the correlation of the first posterior shift in the CoP to step length was significantly stronger in the FOG group. This means that the consequences of a smaller posterior shift during the APA phase impacted the first step to a greater extent in the participants with FOG than those without FOG. This problem may be exacerbated by the time the second step was taken, as the second step was significantly shorter in the FOG group. This may be another indicator to support the sequence effect hypothesis of FOG [36, 37], unfortunately, we were unable to capture more than the first two steps.

The conditions of the center of mass (CoM) at toe-off should predict the first step placement, according to studies on healthy controls, but in PD the APA is diminished, and thus CoM speed is diminished at toe off. Although the APA was similar in our two PD groups, the differences in step placement were significantly different, suggesting that one of our groups deviated from the expected placement based on the APA. The nFOG group took a narrower step with more step width variability and a non-significantly shorter first step, which could indicate a mid-step adjustment occurring to account for their parkinsonian APA [16, 19]. Alternatively, the FOG group may have an additional impedance in their step execution that course-adjusted their step length to decrease and increase their step widths. Future studies could incorporate models [16] to predict where the step should land based on the parkinsonian APA and perhaps illuminate where the step is being affected. Additionally, in controls, the second step is independent the APA, and people employ a one-step-at-a-time strategy [16,18]. In our study, in the FOG group, the conditions at the end of the first step appear to exacerbate the effects of PD on the second step, as the second step was significantly slower and wider, with less toe clearance than the nFOG group.

Taken together, our findings are consistent the idea that start hesitation and FOG during gait initiation may be associated with impairment in the transition from the APA to stepping. Transitions in motor behavior, such as turning, obstacle avoidance and gait initiation are common precipitants of freezing events [1, 42]. In each of these examples, the intended movement involves a change in direction or state that requires either an anticipatory or reactive alteration in posture to ensure whole body stability. Yet the successful execution of transitions demands flexibility and adaptability in posture-locomotor coupling so that changes in limb trajectory are not rigidly-locked pre-set adjustments in posture. Our findings suggest that a lack of flexibility or an additional impedance in the coupling between posture and locomotion may differentiate those with FOG from those without FOG. Evidence for this idea comes from experiments showing that the capacity to alter APAs in response to changes in stance width is significantly reduced in people with PD [35]. Similarly, when a lateral tug on the pelvis was provided to assist the lateral APA movement, the APA duration, time to first heel-off, and step duration decreased, but step length remained the same [13], again suggesting that the APA may be decoupled from step execution in people with PD [43]. Our study additionally suggests that step length is related to the posterior CoP shift for PD with and without FOG, but the slope of this relationship was stronger in PD with FOG. Additional cognitive load, such as dual-tasking, exacerbates the problem by increasing the level or variability of APA impairment [24], which may be followed by a diminished capacity in those with FOG to adapt the step to overcome the altered APA.

Limitations

The findings of this study should be interpreted with some caution since the FOG and nFOG cohorts were matched in age and UPDRS measures of disease severity, but not matched in disease duration or medication dosage (albeit they were tested off medication). Thus, the results could reflect, in part, differences in medication wash-out. Our sample was also restricted to those without significant levels of tremor, so the results are applicable to those with a predominantly akinetic-rigid presentation of disease. We do not have sufficient information to classify our participants into sub-phenotypes of festination experienced [44], or into subtypes of FOG (affective, cognitive, or motor) [15], but future studies should consider these characterizations. In particular, freezing may be worsened by cognitive impairment, anxiety, or asymmetry of disease presentation. These confounders may exacerbate freezing by additionally decreasing a person’s ability to overcome a diminished APA and execute an effective step. Unfortunately, there were no trials of self-initiated gait where a participant froze during data collection.

Due to the number of variables investigated, there was an increased potential for a Type I error. We tried to minimize this potential issue by limiting our correlations analysis *a priori* to relationships of specific interest within the sagittal or frontal planes. The small sample size limits the conclusions that can be drawn from the correlations, so to limit the probability of Type I error, the multiple linear regression was chosen for the conservative nature of its interaction term. In addition, we did not systematically control or vary the initial conditions (e.g., stance width) or APA magnitudes within-subjects. For this reason, differences in the relationship of APAs and stepping were derived from the variance between-subjects. Additional studies are needed (similar to those of Rocchi et al. 2006 [35] and Mille et al.

2007 [13]) that examine the within-subjects effects of initial conditions or response to imposed motor or cognitive (dual-tasking) changes on the APA.

Conclusions

Despite similar impairments in the capacity to generate an APA, the performance of gait initiation in the group with FOG was characterized by reduced step lengths, increased step widths, reduced toe-clearance, and stronger relationships between the initial conditions (stance width) or the posterior shift of the APA and the first step kinematics. Although correlations with our small sample sizes should be interpreted cautiously, this means that consequences of alterations in the APA may be greater in people with FOG than those without FOG, with similar initial stance widths leading to larger step widths in PD with FOG, and with the FOG group having step lengths strongly correlated to their 1st A-P CoP shift. Impairment in the capacity to appropriately adapt the locomotor (stepping) pattern to changes in postural set, particularly during transitions in behavior and/or with additional cognitive load, may precipitate FOG events.

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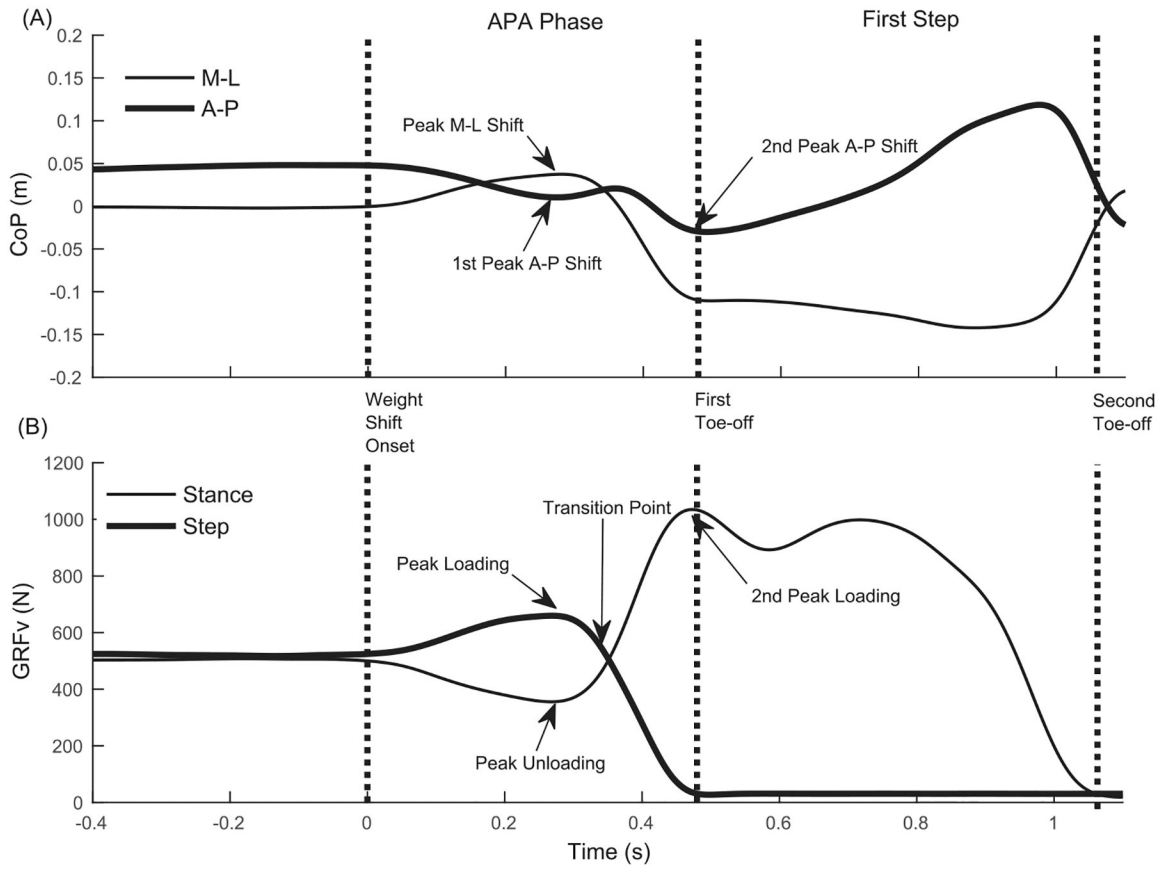

Fig. 1.

Example plots of a clear APA in Gait Initiation including (A) CoP M-L and A-P and (B) GRFv of Step and Stance leg. Key APA points are labeled.

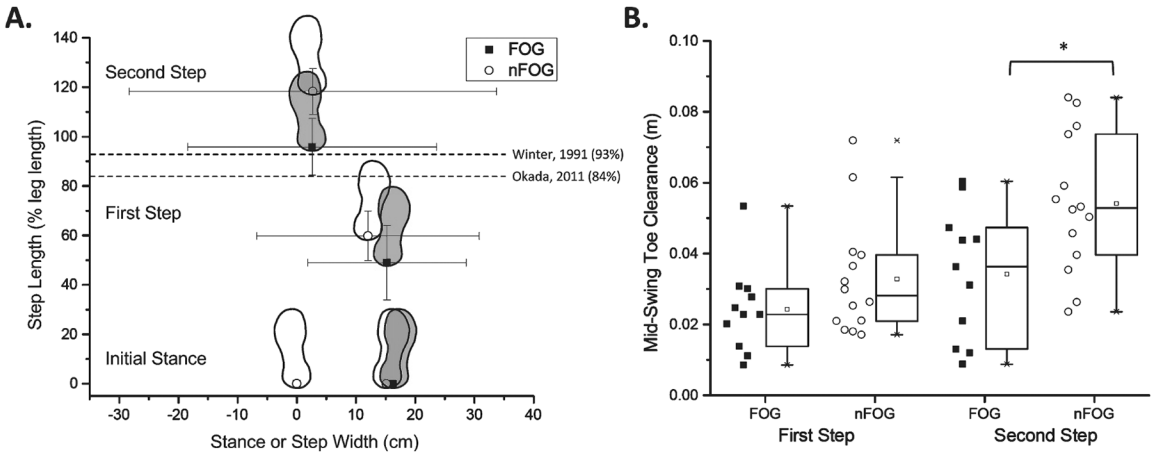

Fig. 2.

First and second step spatial characteristics for people with FOG (black squares) and without FOG (nFOG, open circles). (A) Graphical representation of the initial stance, and first and second step widths and lengths. Footprints demonstrating step landings are scaled to the y-axis only. The initial stance leg is represented by the left markers placed overlapping at (0,0) while the first step leg is represented by the markers to the right demonstrating the mean stance widths of the two groups (error bars have been left off for tidiness). The mean first step widths and lengths are measured from the initial stance leg heel marker, and mean second step widths and lengths were measured from the location of the first step heel marker. Error bars are the average of the within-subjects variance. Significant difference markers were omitted for tidiness, but differences ($p < 0.05$) were seen between groups in first step width and second step length and width (although the second steps landed at similar locations compared to baselines, the widths were different). The two dashed lines demonstrate previous reports of first step length in healthy adults [26, 38]. (B) Box plots showing the step toe clearance during mid-swing for the two groups, first and second steps. *A significant difference ($p < 0.05$) was seen between groups for the 2nd step clearance.

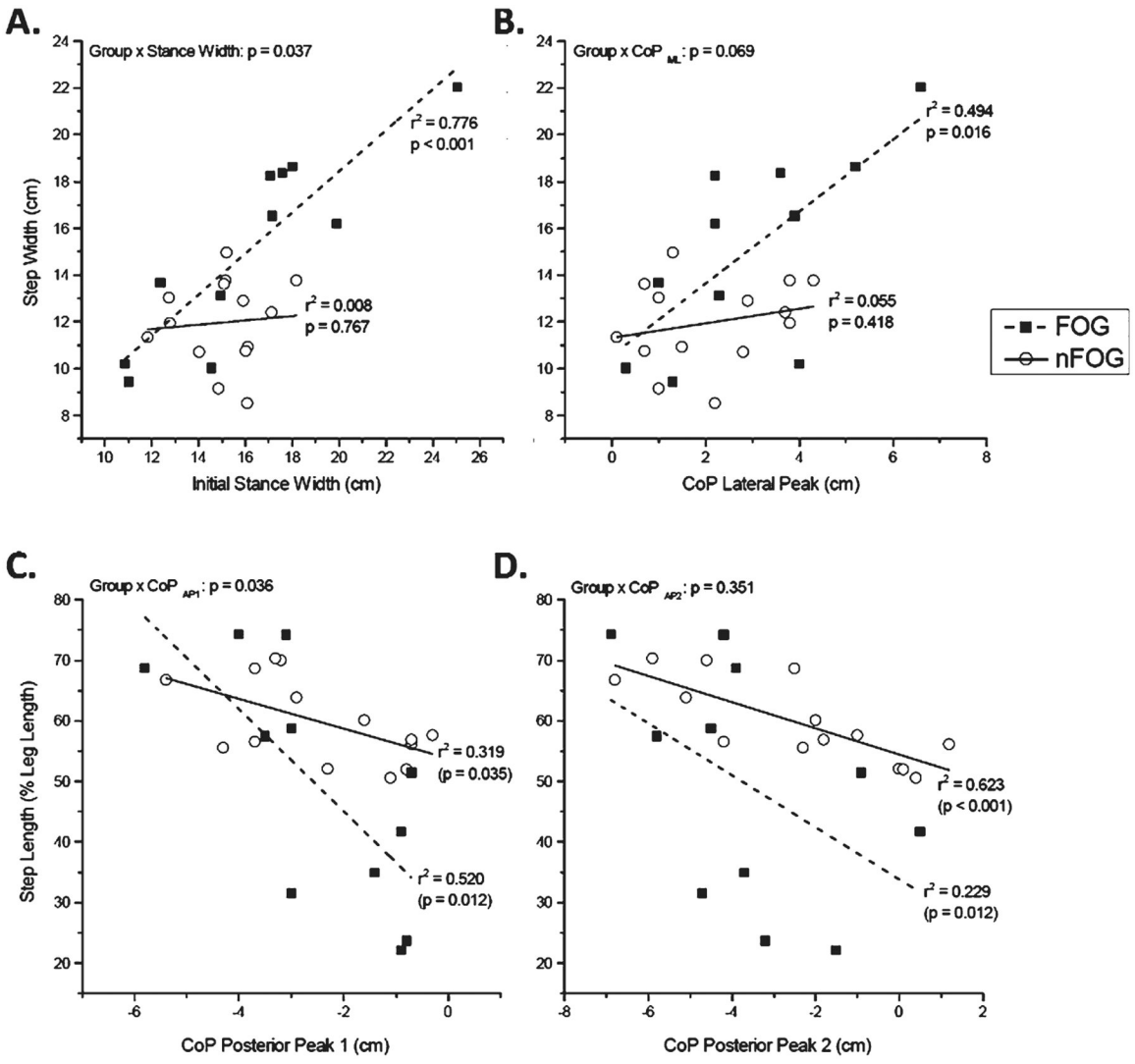

Fig. 3.

Correlation analysis results for: (A) first step width vs. initial stance width; (B) step width vs. CoP lateral peak; (C) first step length vs. CoP posterior excursion (peak 1) and (D) first step length vs. CoP posterior excursion (peak 2). Correlation coefficients and related *p*-values are shown near each line of best fit, with the *p*-values for the interaction terms from the multiple linear regressions shown at the top of each plot. FOG group = black squares, dashed lines; nFOG group = open circles, solid lines.

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Table 1

Gait Initiation Results of one-way ANOVAs on FOG group for kinetics, kinematics, and associated timings

	nFOG (N = 14)	FOG (N = 11)	F	*p*
	Mean ± Standard deviation			
Kinetics				
APA Kinetics				
Percent of trials with an APA	84.5 ± 25.5	90.5 ± 19.5	0.41	*0.527*
Peak CoP_{ML} excursion (cm)	2.1 ± 1.4	3.0 ± 1.9	1.61	*0.218*
Peak CoP_{ML} excursion CV (%)	68 ± 48	58 ± 46	0.29	*0.597*
1st Peak CoP_{AP} excursion (cm)	2.4 ± 1.6	2.5 ± 1.7	0.003	*0.958*
1st Peak CoP_{AP} excursion CV (%)	70 ± 46	55 ± 27	0.89	*0.356*
Peak GRF_V loading of step foot (%BW)	8.4 ± 5.6	12.2 ± 7.0	2.22	*0.150*
Peak GRF_V loading of step foot CV (%)	82 ± 78	62 ± 44	0.58	*0.454*
Peak GRF_V unloading of stance foot (%BW)	8.5 ± 5.6	12.8 ± 7.6	2.60	*0.121*
Peak F_V unloading of stance foot CV (%)	81 ± 79	60 ± 45	0.63	*0.435*
2nd Peak CoP_{AP} excursion (cm)	2.5 ± 2.5	3.5 ± 2.2	1.24	*0.277*
2nd Peak CoP_{AP} excursion CV (%)	296 ± 757	78 ± 130	0.89	*0.355*
Time to transition point (ms)[^]	473 ± 60	479 ± 168	0.01	*0.911*
Time to transition point (%)	22 ± 11	25 ± 14	0.31	*0.585*
1st **Step Kinetics**				
Time to 1st step toe-off (ms)	749 ± 104	728 ± 281	0.07	*0.800*
Time to 1st step toe-off CV (%)	17.5 ± 5.5	19.7 ± 13.4	0.31	*0.582*
Time of transition point to toe-off (ms)	447 ±195	390 ± 217	0.47	*0.499*
Time of transition point to toe-off CV (%)	33 ± 20	25 ± 22	1.05	*0.317*
2nd **Step Kinetics**				
Time to 2nd step toe-off (ms)	1342 ± 133	1368 ± 245	0.19	*0.668*
Time to 2nd step toe-off CV (%)	11.1 ± 4.1	12.6 ± 8.5	0.33	*0.569*
2nd Peak GRFV loading of stance foot (%BW)	50.6 ± 9.0	47.9 ± 4.6	0.78	*0.387*
2nd Peak GRFv loading of stance foot CV (%)	11 ± 7.5	11 ± 7.2	0.003	*0.954*
Kinematics				

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	nFOG (N = 14)	FOG (N = 11)	F	*p*
	Mean ± Standard deviation			
1st Step Kinematics				
Initial stance width (cm)	15.1 ± 1.7	16.2 ± 4.2	0.88	*0.358*
1st Step length (% leg length)	59.8 ± 6.9	49.0 ± 19.4	3.77	*0.064*
1st Step length CV (%)	10.0 ± 5.4	15.1 ± 10.6	2.42	*0.133*
1st Step width (cm)	**12.0 ± 1.9**	**15.2 ± 4.1**	**6.47**	**0.018** *
1st Step width CV (%)	**18.8 ± 6.1**	**13.4 ± 6.1**	**4.81**	**0.039** *
1st Step mid-swing toe clearance (cm)	3.3 ± 1.6	2.4 ± 1.2	2.10	*0.161*
1st Step mid-swing toe clearance CV (%)	40.5 ± 25.0	32.4 ± 12.3	0.97	*0.335*
1st Step duration (toe off to contact) (s)	0.67 ± 0.08	0.63 ± 0.09	1.93	*0.178*
1st Step duration CV (%)	11.1 ± 4.7	11.6 ± 7.3	0.05	*0.823*
1st Step speed (cm/s)	81.9 ± 17.3	71.7 ± 29.3	1.17	*0.290*
1st Step speed CV (%)	12.9 ± 5.4	13.7 ± 7.1	0.09	*0.762*
2nd Step Kinematics				
2nd Step length (% leg length)	**58.5 ± 8.4**	**46.9 ± 18.1**	**4.61**	**0.043** *
2nd Step length CV (%)	9.2 ± 4.1	11.5 ± 7.7	0.90	*0.354*
2nd Step width (cm)	**9.3 ± 2.0**	**12.6 ± 4.6**	**5.69**	**0.026** *
2nd Step width CV (%)	31.1 ± 15.9	21.0 ± 12.0	3.08	*0.093*
2nd Step mid-swing toe clearance (cm)	**5.4 ± 2.0**	**3.4 ± 1.9**	**6.69**	**0.017** *
2nd Step mid-swing toe clearance CV (%)	47.6 ± 26.0	49.8 ± 26.3	0.043	*0.838*
2nd Step duration (toe off to contact)	0.90 ± 0.08	0.83 ± 0.08	4.25	*0.051*
2nd Step duration CV (%)	11.9 ± 7.1	11.6 ± 6.9	0.007	*0.934*
2nd Step speed (cm/s)	59.7 ± 10.4	51.1 ± 18.5	2.17	*0.154*
2nd Step speed CV (%)	13.8 ± 4.6	14.4 ± 6.6	0.07	*0.798*

Mean (standard deviation) for each variable and for each group. F-statistics (*p*-values) are given in the statistics column.

* (and bolded font) denotes a significant difference ($p < 0.05$) between FOG and nFOG.

^ Times to transition point only include trials with an APA, while other times include all trials (trials without an APA, the weight shift onset and transition point were defined as the same time point).