Center of Mass trajectories during turning in patients with Parkinson's disease with and without freezing of gait

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Conflict of interest statement

The authors have no conflict of interest to disclose.

Abstract

Background: Despite the strong relationship between freezing of gait (FOG) and turning in Parkinson's disease (PD), few studies have addressed specific postural characteristics during turning that might contribute to freezing.

Methods: Thirty participants with PD (16 freezers, 14 non-freezers) (all tested OFF medication) and 14 healthy controls walked 5 meters and turned 180^0 in a 3D gait laboratory. COM behavior was analyzed during four turning quadrants of 40^0 between 10^0-170^0 pelvic rotation and during 40^0 before actual FOG episodes. These pre-FOG segments were compared with similar turning sections in turns of freezers without FOG. Outcome parameters were turn time, COM distance, COM velocity, step width and the medial- and anterior COM position.

Results: Turn time was increased in freezers compared to non-freezers (p=.000). No differences were found regarding COM distance and velocity during turning quadrants between groups and between freezers' pre-FOG segments and similar turning segments without FOG. Medial COM deviation was reduced in PD patients compared to controls (p=.004), but no differences were found between freezers and non-freezers. In turns with freezing, turn time increased (p=.005) and step width decreased (p=.025) pre-FOG. Freezers also showed a less medial (p=.020) and more anterior (p=.016) COM position pre-FOG compared to turning sections without FOG.

Conclusions: Our results revealed no subgroup differences in COM behavior during uninterrupted turning. However, we found a reduced medial deviation, a forward COM shift and a decreased step width in freezers just before FOG episodes. These abnormalities may play a causal role, as they could hamper stability and fluent weight shifting necessary for continued stepping during turning.

Keywords:

Parkinson's disease, dynamic stability, turning, freezing of gait, center of mass

1. Introduction

Freezing of gait (FOG) is a common and debilitating gait disturbance in patients with Parkinson's disease (PD)[1]. FOG is defined as the inability to maintain stepping behavior when having the intention to walk[2] and has been shown to occur most frequently during turning[3]. Despite the strong relationship between FOG and turning, few studies have evaluated the specific postural characteristics of the turning movement that may contribute to FOG[4–6].

Thirty-five to 45% of all steps during daily life activities are made during turning movements[7]. In healthy subjects, turning is characterized by a decreased step length, prolonged stance phase of the inner leg and an increased swing velocity of the outer leg. A turn is initiated by rotation of the head, followed by a the trunk, pelvis and feet which move towards the inner side of the turn (top-down coordination)[8]. Moreover, in healthy subjects the Center of Mass (COM) deviates to the inner side of the turn, a pattern which becomes more exaggerated with increasing turning speed[9]. With ageing, turning is performed more slowly and the COM less medially oriented[8].

In PD, turning is already impaired in the early stages of the disease, independent of FOG[4]. The turning-arc enlarges and more time and steps are needed to complete a turn[4]. Besides these spatiotemporal impairments, the initiation of head orientation is postponed, inducing an increased coupling of head and trunk rotation compared to the top-down coordination in healthy controls[6]. Moreover, turning problems in PD are correlated with balance impairments, falls and FOG[10].

The asymmetric nature of the turning task, demands more bilateral coordination[11]. Plotnik et al. found that freezers have already more gait asymmetry during straight-line walking than non-freezers, irrespective of the disease-dominant side[12]. This deficit may become exaggerated during an asymmetric task such as turning. Our group recently demonstrated that during asymmetrical gait on a split-belt treadmill, freezers showed reduced adaptation of step parameters and moreover, as a result, FOG-episodes were elicited[13]. Hence, the increasing demand on bilateral coordination may partly explain the triggering of FOG during turning[14,15].

Another hypothesis is that FOG during turning is triggered by lack of medial COM deviation. During turning, the COM movement must be controlled in the medio-lateral (ML) plane to enable fluent continuation of stepping. During en-bloc turning, lack of medial COM deviation may be associated with an incomplete weight shift to the inner side of the turning arc, affecting toe clearance of the outer leg, which could contribute to FOG[16]. Quite apart from turning, dynamic stability in the ML direction was found to be affected in PD[17] and in freezers this correlated with FOG severity[18],

which may also interact with turning deficits. This is the reason why physiotherapists encourage exaggerated weight shifting in freezers to avoid or prevent FOG[19].

To our knowledge, no kinematic studies have been performed to understand differences in COM behavior during turning between freezers and non-freezers and whether this contributes to FOG. In the current study, we examined COM behavior in healthy elderly and PD patients with and without FOG during 180° turning. Most research on FOG is based on behavioral comparisons between freezers and non-freezers, who are matched for disease-related parameters. However, this paradigm is not ideal due to the inherent differences in disease profiles of these subgroups[20]. Therefore, we also conducted an analysis relating to the FOG-episodes itself. We investigated COM behavior immediately before FOG episodes to understand the precipitating factors that prevent normal stepping during turning. We expected to find less medial COM deviation in patients with freezing relative to their non-freezing counterparts and that this phenomenon would be exaggerated just before FOG episodes.

2. Methods

2.1. Participants

Thirty patients with PD, who also participated in previous turning experiments[16,21], were included in the study if a complete set of data were obtained to perform COM trajectory analysis. Patients were classified as a freezer (FR) (n=16) or non-freezer (NFR) (n=14) based on the first question of the New Freezing of Gait Questionnaire (NFOG-Q) (FR: item 1 ≥ 1). Fourteen age-matched healthy control subjects (HC) were recruited to provide reference values on COM- and ankle positions during turning. All participants were able to walk 10 meters, were able to turn independently while OFF medication, had MMSE scores ≥24 and no comorbidity affecting gait. All participants provided written informed consent and the study was approved by the research Ethics Committee of the University Hospitals Leuven according to the Declaration of Helsinki.

2.2. Protocol and data collection

Data were collected using an eight camera VICON 3D motion capturing system (Vicon Motion System, workstation 612). Thirty-one retroreflective markers (diameter 14mm) were placed according to the full body plugin gait marker configuration (VICON, Oxford Metric, Oxford, UK). Sample frequency was 100Hz. Polygon software (Vicon, version 3.1) was used for visualization of FOG episodes. Detection of FOG trials was done by two independent raters, blinded for NFOG-Q-scores[21](for details, see Supplementary Methods). PD patients were tested in the practically defined OFF-state, i.e. 12-15 hours after the last medication intake. All participants were instructed to walk 5 meters and turn 180^0 at comfortable speed. Two retroreflective markers placed 0.5m from each other indicated where patients had to turn and standardized the turning arc [16] (Fig. 1a). Turns to the left and right side were performed three times and were counterbalanced.

Insert Figure 1 about here

2.3. Data analysis

2.3.1. COM behavior during turning quadrants

COM was defined as the centroid of the lower limb, pelvis, trunk, head and arm segment masses, calculated in Nexus software. Ankle movements were registered by markers on the lateral malleoli. Turns were analyzed between 10° and 170° of pelvic rotation in relation to laboratory axes, avoiding stretches of non-turning gait at the beginning (0-10°) and end (170-180°) of the turn[16]. Fig. 1b illustrates that COM and ankle movements were analyzed for four turning quadrants, each consisting of 40° pelvic rotation, defined as the angle between the sagittal axis of the pelvis and the sagittal

laboratory axis[16]. Outcome parameters were turn time, COM distance, COM velocity and the medial- and anterior COM position in relation to the ankles within each quadrant. Additionally, to control for differences in pelvic- and step width, we investigated a proxy measure for step width, defined as the distance between the markers on the lateral malleoli.

The anterior position of the COM was defined as the distance of the COM in front of an imaginary line between the lateral malleoli. The higher this value, the more anterior the COM was located in relation to the ankles. The medial position of the COM was defined as the distance of the COM to the middle of an imaginary line between the lateral malleoli *(See supplementary methods for more information)*. A medial COM position of zero indicates that the COM is located exactly between the ankles. The more negative the value of ML COM position, the more medially the COM was deviated during turning.

Turn time and COM distance were calculated as the sum of travelled distance by the COM at all time-points within a particular turning quadrant. COM velocity, step width and medial- and anterior COM positions were averaged over all time points within a turning quadrant. Turns with FOG episodes were excluded for these analyses. This led to exclusion of 1/6 turns in 3 freezers, 2/6 turns in 1 freezer and 4/6 turns in 1 freezer.

2.3.2. *COM behavior pre-FOG*

COM behavior was also analyzed immediately before a FOG-episode (pre-FOG) (Fig. 1c). Therefore, the pelvic rotation angle at the start of each freezing episode was determined. Next, the 40° turning quadrant (also based on pelvic rotation) before this starting point was analyzed. The start and end of each FOG episode were detected by combining video (3D) images with visual inspection of the knee-angle data (flexion-extension)[16]. The onset of an episode was defined as the start of a delayed knee flexion; termination of an episode was determined when at least two consecutive normal gait cycles were regained[16]. This procedure was tested for reliability previously[21]. To compare pre-FOG segments, comparable 40° sections based on the same degrees of pelvic rotation within the same patient were analyzed for turns without freezing (Fig. 1d). Outcome parameters were the same as during the between group analysis.

2.4. Statistical analysis

Statistical analyses were performed using SPSS (version 22) with an alpha of 5%. For the between groups analyses, means of three left and three right turns were calculated. Since there was no

influence of disease-dominant or turning side[16], all turns were pooled and averaged. To compare turning characteristics between groups, MANOVA was used with Tukey HSD post-hoc comparisons. For the within-group analysis, 40° degrees of turning pre-FOG were compared with the same 40° degrees of turning in a non-freezing trial of the same subject using a linear mixed model with subject as a random factor.

3. Results

3.1 Participants

Subject characteristics are shown in Table 1. All groups were matched for age and gender. There were no differences between FRs and NFRs regarding disease duration and disease severity measured by the motor part of the Unified Parkinson's Disease Rating Scale (revised version by the Movement Disorder Society) (MDS-UPDRS-III) and the Hoehn & Yahr (H&Y) disease stage. Medication dose, indicated by the Levodopa Daily Dose (LEDD), did not differ between FRs and NFRs. Out of 16 FRs, six FRs froze during the actual 180° turns.

Insert Table 1 about here

3.2.1. COM behavior during turning quadrants – between group analysis

Table 2. shows the COM behavior in FRs, NFRs and HCs during turning (10^0-170^0). Turn time was different between groups in all quadrants (Table 2a). Post-hoc analysis showed longer turn times for FRs compared to NFRs in the first quadrant (10^0-50^0) (p=.018) and the entire turn (10^0-170^0) (p=.010). FRs demonstrated longer COM turn times compared to HCs during all quadrants (p=.000-.002) and the entire turn (p=.012). No significant differences between NFRs and HCs were found. Surprisingly, no differences were found regarding COM distance and COM velocity between groups during turning. (Table 2b-c). Step width was different between groups in all quadrants (Table 2d). Post-hoc analysis showed smaller step widths for FRs compared to NFRs in the 4^{th} (130^0-170^0) quadrant (p=.035) and entire turn (10^0-170^0) (p=.042). Step width in HCs was larger compared to FRs (p=.000-.001) and NFRs (p=.000-.025) during all turning quadrants. Table 2e shows the differences across groups in medial COM position during 10^0-50^0 (p=.005), 90^0-130^0 (p=.006) and the entire turn (10^0-170^0) (p=.004). Post hoc analyses showed no differences between FRs and NFRs. In HCs the COM was more medially positioned compared to both FRs (p=.017-.048) and NFRs (p=.004-.012). No differences were found regarding anterior COM position during turning quadrants (Table 2f). Fig. 2a-c show representative turns of a HC and a freezer without and with FOG respectively, visualizing the COM and ankle trajectories during turning. Both step width and medial COM deviation decreased when comparing the turn of the HC (fig 2a) with a representative FR without freezing (2b) and the FR without freezing with a representative FR with freezing (2c). Figure 2d shows an atypical example of a FOG episode accompanied with festination.

Insert Table 2 about here

Insert Figure 2 about here

3.2.2. COM behavior pre-FOG - within-group analysis

Six of the 16 freezers had a total of 21 freezing-episodes during turning. Most FOG episodes occurred in the 4th quadrant (47.6%), followed by the 3rd (28.6%), 2nd (14.3%) and 1st quadrant (9.5%). Table 3 shows the results of the paired analyses between 40° pre-FOG segments and comparable segments without FOG. FOG-episodes within the same subject did not show a characteristic pattern. Turn time was increased in the pre-FOG compared to similar turning sections without FOG (p=.005). No differences were found regarding COM distance and COM velocity. Interestingly, in pre-FOG segments, step width decreased (p=.025) and the COM was positioned less medially (p=.020) and more anteriorly (p=.016) compared to similar turning sections without FOG. In one subject (subject 6 and FOG episode 21, see also figure 2d), COM velocity and step width were particularly increased and the COM was positioned less medially and more anteriorly compared to the other subjects. When we investigated this in more detail by visually inspecting the 3D videos of this patient, we noticed a pattern of hastening and festinating pre-freezing behavior. When we repeated the analysis without this patient, however, significant results remained.

Insert Table 3 about here

4. Discussion

The goal of the current study was to investigate COM behavior during turning in patients with and without FOG to better understand the striking association between FOG and turning[6,16,21]. We were particularly interested whether a reduced medial COM shift would predict FOG. At the group level, our results revealed no clear alterations of COM between freezers and non-freezers, except for increased COM turn times and narrower step widths in freezers. However, immediately before a FOG episode, COM turn time increased and the COM was less deviated medially and more anteriorly, confirming our hypothesis. An unexpected finding was that step width, or a proxy of this parameter, became narrower just before FOG.

The finding that both freezers and non-freezers needed more time to complete a turn than controls is in accordance with the literature and our earlier findings[4,6]. Strikingly, COM turn time in freezers was only increased in the first quadrant relative to non-freezers. This suggests that freezers may have more difficulty in initially adapting the turn and switch their motor pattern to the asymmetrical demands. This also coincides with a recent study from our group, showing that freezers adapted more slowly to an asymmetrical task, such as split-belt walking, compared to non-freezers[13].

Unexpectedly, we found that freezers, irrespective of FOG, adopted a narrower step width during turning, particularly in the last two turning quadrants, which became even narrower just before a FOG episode. We used the distance between lateral malleoli as an estimate of step width, whereas in a previous study, step width was measured using consecutive footfall data during turning [14]. This earlier study also showed that HCs and non-freezers increased their step width during 180^0 turning compared to straight-line walking. In contrast, freezers did not change their step width[14]. Before obstacle crossing, Galna et al demonstrated that patients with PD, irrespective of subgroup, also widened their base of support[22].

In the current study, an adaptive widening of the base of support before a FOG-episode was not shown, but the opposite. We found a pre-FOG narrowing of step width which may indicate that freezing already occurs proximally, i.e. that loss of weight shifting amplitude is part of freezing. In addition, a narrow base of support may negatively influence ML weight shifting and adequate unloading of the swing limb, thus having a negative impact on the continuation of stepping. Mensink et al. showed that when providing extra weight to patients with FOG using a weighted vest during walking, FOG was more frequent. However, unloading the body using bodyweight support did not reduce FOG-frequency during gait[23]. The failure to increase step width prior to FOG may further compromise dynamic stability and may explain why recent studies associated FOG with a higher risk of falling[24,25].

As well as reduced step width, we found a less medial and more anterior position of the COM during turning sections prior to FOG. These results are consistent with a previous study, which indicated poorer anterior-posterior directional control during a voluntary weight-shifting task in freezers compared to non-freezers when ON medication[26]. The more anterior and less medial position of the COM in one subject, together with the highly increased COM velocity was indicative of festination preceding FOG as described by Nutt et al.[2]. This tendency of the COM to move forward may also imply a greater fall risk.

As for the reduced medial COM deviation, Nantel et al. showed that weight shifting difficulties in the ML direction during stepping in place was highly correlated with FOG severity[18]. In line, Jacobs et al. showed that freezers needed multiple anticipatory postural adjustments (APAs) after a backward platform perturbation to produce corrective steps compared to HCs, who needed just a single APA [27]. Delval et al. demonstrated that in addition to this abnormal APA behavior during platform perturbations, freezers also had multiple and abnormal APA's during gait initiation compared to NFRs and HCs[28]. These findings, together with the reduced medial COM position found in the current study, suggest a postural control impairment in freezers, which may also contribute to FOG during turning.

Reduced medial COM movement could also signify a conservative strategy to maintain balance during turning in line with an en-bloc turning strategy[5,6]. Normal medial COM deviation creates sufficient centrifugal forces to allow body rotation, especially immediately after the pivot point at 90°[9]. Overall, PD patients in our study did not shift their COM as far as HCs towards the inner side of the turn. As dynamic stability is already compromised in PD[17,29], subjects may have shown more careful behavior during turning.

COM deviation to the inner side of the turning cycle has previously been found to be related to turning velocity, in that a less medial position was associated with lower velocity[9]. However, in the current study, COM velocity during turning was not different between subgroups with and without FOG, and also not in the within-group paired segment analysis. This would suggest that the alterations of COM deviations per se are not explained by velocity. This study was limited by a low frequency of FOG-episodes, which may have influenced the power of the pre-FOG segments. However, this problem has been reported in many other FOG studies[2].

From a clinical perspective, turning in laboratory settings is different from turning situations in daily life. However, offering patients specific turning strategies in the context of their rehabilitation could provide tools to overcome abnormal COM behavior and prevent FOG. The current study would suggest to focus on moving the COM to a more medial position during turning, as well as consciously

widen step width. However, Bhatt et al. showed that turning sharpness influenced FOG-frequency negatively[14]. Strategies to increase step width may therefore be the preferred approach to reduce the number of freezing episodes.

5. Conclusion

The current study showed a reduced step width in freezers versus non-freezers in turns in which no FOG was apparent. This finding became even more pronounced in turning sections preceding actual freezing episodes together with a reduced medial deviation and increased forward progression of the COM. These COM abnormalities hamper stability and fluent weight shifting necessary for continued stepping during a turn.

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Table 1. Subject characteristics.

	FR (n=16)	NF (n=14)	HC (n=14)	p-value
Age (years)	68.71(7.45)	66.57(7.37)	65.29(6.72)	.537
Gender (% male)	75.0	71.4	85.7	.505
MMSE (24-30)	27.71(1.14)	28.71(1.20)	29.07(1.27)	.012*
Duration PD (years)	9.53(4.40)	7.79(4.84)	NA	.338
H&Y (0-5)	2.53(0.46)	2.31(0.46)	NA	.061
MDS-UPDRS III (0-132)	37.85(13.99)	34.5(9.94)	NA	.573
NFOG-Q(0-29)	13.5(8.26)	0(0)	NA	NA
LEDD (mg/day)	567(235)	472(171)	NA	.220

Demographic and disease characteristic (in OFF) for each group. Mean (SD) are presented (* p <.05).

MMSE: Mini Mental State Examination

H&Y: Hoehn & Yahr disease stage

MDS-UPDRS: Unified Parkinson's disease rating scale (revised version by Movement Disorder Society)

NFOG-Q: New Freezing of Gait Questionnaire

LEDD: Levodopa daily dose

Table 2. COM behavior during turning quadrants.

	FR (N=16)	NFR (N=14)	HC (N=14)	p-value
a. Turn Time (s)				
10^0-50^0	0.80(0.17)§	0.67(0.11)	0.60(0.08)	.000*
50^0-90^0	0.55(0.23)	0.43(0.09)	0.34(0.04)	.002*
90^0-130^0	0.57(0.26)	0.44(0.10)	0.36(0.04)	.003*
130^0-170^0	0.90(0.27)	0.68(0.17)	0.51(0.09)	.000*
10^0-170^0	2.82(0.89)§	2.21(0.44)	1.80(0.18)	.000*
b. COM Distance (cm)				
10^0-50^0	4.25(0.64)	4.16(0.62)	4.69(0.76)	.100
50^0-90^0	1.84(0.27)	1.75(0.25)	1.81(0.19)	.546
90^0-130^0	1.64(0.27)	1.62(0.30)	1.66(0.32)	.952
130^0-170^0	3.73(1.20)	3.57(1.05)	3.14(0.70)	.270
10^0-170^0	11.46(1.55)	11.10(1.84)	11.30(1.08)	.814
c. COM velocity (cm/s)				
10^0-50^0	7.22(3.90)	7.06(3.52)	8.34(2.09)	.492
50^0-90^0	6.55(4.23)	6.09(3.52)	8.04(3.27)	.359
90^0-130^0	5.96(3.92)	5.21(2.16)	6.37(2.28)	.575
130^0-170^0	6.39(3.65)	6.08(2.90)	6.82(2.27)	.807
10^0-170^0	6.53(3.89)	6.12(2.77)	7.39(2.38)	.554
d. Step width (cm)				
10^0-50^0	30.25(4.77)	33.50(3.94)	38.56(3.85)	.000*
50^0-90^0	26.14(4.31)	28.96(3.32)	35.08(3.34)	.000*
90^0-130^0	25.24(4.76)	27.86(3.21)	32.47(4.89)	.000*
130^0-170^0	27.27(4.99)§	31.47(4.44)	34.18(3.67)	.000*
10^0-170^0	27.23(4.42)§	30.44(3.41)	35.07(2.15)	.000*
e. Medial COM postition (cm)				
10^0-50^0	-3.64(1.74)	-2.84(2.65)	-5.59(1.96)	.005*
50^0-90^0	-5.38(1.88)	-4.32(4.50)	-6.66(2.78)	.162
90^0-130^0	-5.19(2.96)	-4.88(3.90)	-8.93(3.82)	.006*
130^0-170^0	-4.63(2.29)	-3.23(3.32)	-5.60(3.95)	.160
10^0-170^0	-4.71(1.18)	-3.82(3.41)	-6.69(1.52)	.004*
f. Anterior COM position (cm)				
10^0-50^0	7.29(2.12)	7.02(0.90)	6.88(1.10)	.752
50^0-90^0	9.43(2.20)	8.72(1.62)	10.08(2.10)	.213
90^0-130^0	10.40(2.05)	9.98(1.57)	8.91(1.78)	.086
130^0-170^0	11.01(1.81)	10.72(1.79)	10.03(1.65)	.312
10^0-170^0	9.53(1.82)	9.11(1.27)	8.97(1.17)	.559

Turn time (a), COM distance (b), COM velocity (c), Step width (d), Medial (e)- and Anterior (f) COM position during turning in FRs, NFRs and HCs. Means and SD per quadrant and entire turn are presented. P-values are shown for MANOVA indicating overall group effects, § indicates significant differences between FRs and NFRs (* p <.05).

Table 3. COM behavior pre-FOG.

FOG episode	Subject	Pre-FOG (^{0}pelvic rotation)	Turn time (s)	Distance COM (cm)	Velocity COM (cm/s)	Step width (cm)	Medial COM position(cm)	Anterior COM position(cm)
1	1	130-170	8.1	32.57	2.69	20.84	-0.59	10.98
2	1	98-138	1.9	15.82	4.53	21.56	-1.59	13.21
3	1	97-137	1.8	10.09	3.53	23.71	-2.77	10.74
4	2	71-111	1.2	15.87	6.08	25.57	-1.09	9.11
5	2	92-132	1.7	12.99	3.83	22.11	-2.41	9.17
6	2	138-178	5	25.66	1.91	23.24	-1.20	9.46
7	2	123-163	4.2	17.78	4.07	22.60	-2.67	10.10
8	2	119-159	2,9	14.11	4.84	23.64	-3.58	9.73
9	2	0-25	NA [a]	NA [a]	4.30	20.82	-1.63	8.49
10	2	66-106	4.2	19.75	3.28	21.92	-5.12	8.55
11	3	83-123	2.7	26.60	2,09	20.54	-2.55	13.67
12	4	53-93	1.1	15.87	7.41	26.37	-7.65	8.98
13	5	31-71	7.1	15.49	1.70	16.79	-1.11	14.56
14	5	148-178	12.4	24.92	1.62	16.08	-3.66	14.99
15	5	32-72	7.6	18.99	1.76	16.47	-1.75	14.30
16	5	136-176	6,1	18.13	2.18	16.30	-4.49	15.31
17	5	86-126	11.4	22.75	1.82	16.87	-2.20	15.05
18	5	43-83	4.9	24.18	1.03	16.51	-0.87	15.81
19	5	0-28	NA [a]	NA [a]	1.90	16.90	-0.65	14.51
20	6	86-126	2.1	20.18	16.36	23.52	-1.93	13.18
21	6	120-160	4.8	20.63	13.68	27.99	0.32	17.84
+ FOG mean (sd)			4.80 (3.31)	19.60 (5.50)	4.32 (3.93)	20.97 (3.66)	-2.37 (1.77)	12.27 (2.90)
- FOG mean (sd)			2.71 (1.36)	21.19 (7.82)	6.66 (7.18)	22.83 (4.83)	-3.64 (2.65)	11.42 (3.06)
p-value			.005*	.450	.138	.025*	.020*	.016*

Turn time, COM distance, COM velocity, Step width and Medial- and Anterior COM position during 40^{0} pre-FOG sections in FRs with (+FOG) and without freezing (-FOG). For +FOG all pre-FOG characteristics are presented for each FOG episode. For both +FOG and -FOG means and SD are presented (* p <.05).[a] *For two pre-FOG segments no full 40^{0} sections were available and therefore turn time and COM distance could not be calculated.*

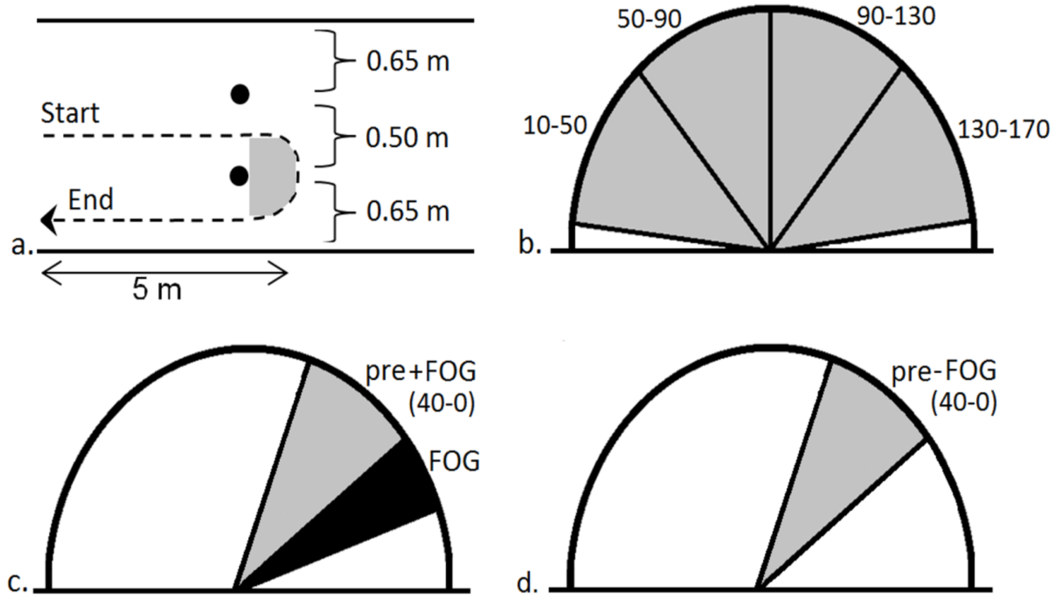

Figure 1. Top view of the walkway. A. Walkway of a right 180^0 turn. Two retroreflective markers (●) were placed in the middle of the walkway. B. For data analysis four turning quadrants between 10^0 and 170^0 of pelvic rotation were analyzed. The vertical line represents the sagittal laboratory axis. The curved line represents the turning trajectory and the straight lines dividing the turning trajectory into the grey turning quadrants represent the sagittal pelvic axis. Each turning quadrant represents 40° of pelvic rotation. C. Exemplary segment of 40^0 pelvic rotation pre-FOG. The black part of the turning trajectory represents a freezing episode. The grey part of the turning trajectory represents the 40° of pelvic rotation before the start of the freezing episode. D. A 40° section of the turning trajectory comparable to the one shown in C was also based on degrees of pelvic rotation.

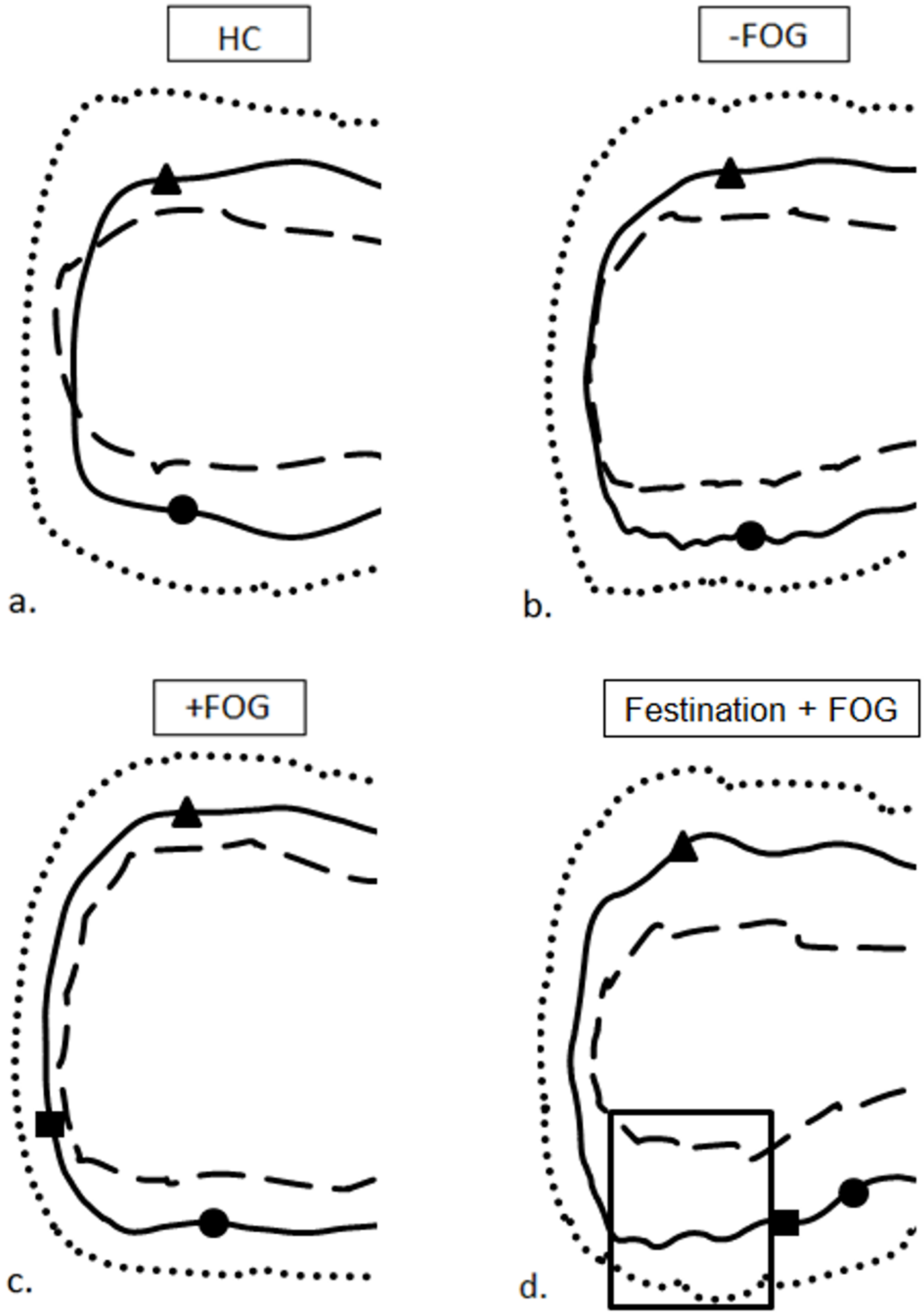

Figure 2. COM behavior during 180^0 turning. A healthy control (a), a freezer without (b) and with (c) freezing, and a turn with festination and freezing (d) during a left 180^0 turn. COM is represented by ▬▬ the left and right malleoli by ••••• and ▬ ▬ respectively. Start (10^0) and end (170^0) of the turn are represented by ● and ▲ respectively. Start of the freezing episode is indicated by ■. The square in figure d. illustrates the festinating behavior during 40^0 pre-FOG in subject 6.

Supplementary methods:

Identification of freezing episodes.

Identification of freezing episodes during turning was performed according to previous work from our research group reported in Spildooren et al. (2010)[1]. Two independent raters, who were blinded for the NFOG-Q score, visually detected the occurrence of freezing episodes during all the trials. If no consensus was obtained, a third rater was included in the evaluation until a consensus between all three raters was obtained. Onset of each freezing episode was based on a visual analysis of the 3D images of a whole body skeleton constructed in Polygon (VICON, ©Vicon Motion Systems Ltd., Oxford, UK) in combination with knee-angle flexion-extension data. After identification of a freezing episode, implying either a complete halt or nearly complete loss of movement), the onset was defined as the start of delayed knee flexion or the onset of a flexion amplitude reduction of >50%. The end of a freezing episode was determined as the time point after which at least two consecutive movement cycles with normal amplitude were regained. This procedure had an inter-rater reliability of 0.95 (p=0.99) as calculated by t Cohen's kappa statistic.

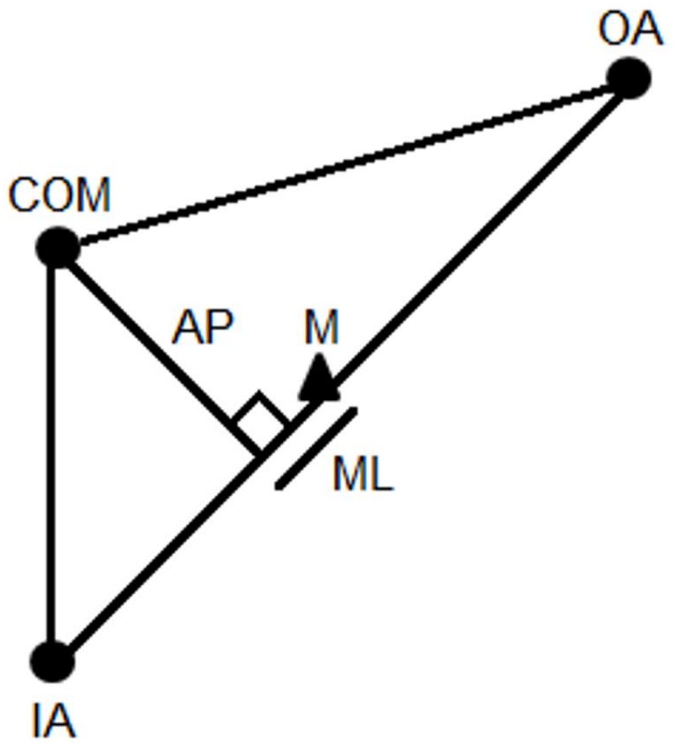

Figure 3. Calculations of the medial- and anterior COM position during turning. Markers on the lateral malleoli are used to calculate the inner ankle (IA) and outer ankle (OA) positions. M represents the middle of the lateral malleoli. ML and AP represent the medial- and anterior deviation of the COM, respectively.

References

1 Spildooren J, Vercruysse S, Desloovere K, Vandenberghe W, Kerckhofs E, Nieuwboer A: Freezing of gait in parkinson's disease: The impact of dual-tasking and turning. Mov Disord 2010;25:2563-2570.