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

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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° in a 3D gait laboratory. COM behavior was analyzed during four turning quadrants of 40° between 10° and 170° pelvic rotation and during 40° 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.

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 [4,5,6].

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 the trunk, pelvis and feet which move toward 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

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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 $1 \geq 1$). 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 14 mm) were placed according to the full body plugin gait marker configuration (VICON, Oxford Metric, Oxford, UK). Sample frequency was 100 Hz. 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 h after the last medication intake. All participants were instructed to walk 5 m and turn 180° at comfortable speed. Two retroreflective markers placed .5 m 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.

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*

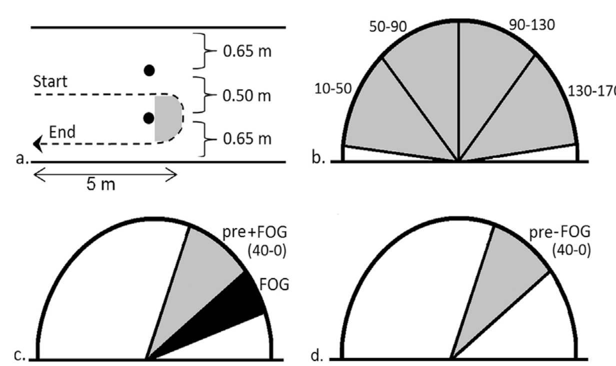

Fig. 1. *Top view of the walkway.* (a) Walkway of a right 180° turn. Two retroreflective markers (●) were placed in the middle of the walkway. (b) For data analysis four turning quadrants between 10° and 170° of pelvic rotation were analyzed. The vertical line represents the sagittal laboratory axis. 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° 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.