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The transition between turning and sitting in patients with Parkinson's disease: A wearable device detects an unexpected sequence of events

Aner Weiss[a], Talia Herman[a], Anat Mirelman[a,f], Shirley Shema Shiratzky[a], Nir Giladi[a,e,f], Lisa L. Barnes[b,c,d], David A. Bennett[b,c], Aron S. Buchman[b,c], Jeffrey M. Hausdorff[a,b,e,*]

[a] Center for the study of Movement, Cognition, and Mobility, Department of Neurology, Tel Aviv Sourasky Medical Center, Tel Aviv, Israel
[b] Rush Alzheimer's Disease Center, Rush University Medical Center, Chicago, IL, USA
[c] Department of Neurological Sciences, Rush University Medical Center, Chicago, IL, USA
[d] Department of Behavioral Sciences, Rush University Medical Center, Chicago, IL, USA
[e] Department of Physical Therapy, Sackler Faculty of Medicine, Sagol School of Neuroscience, Tel Aviv University, Tel Aviv, Israel
[f] Department of Neurology, Sackler Faculty of Medicine, Sagol School of Neuroscience, Tel Aviv University, Tel Aviv, Israel

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ABSTRACT

Background: When older adults turn to sit, about 80% of the subjects complete the turn before starting to sit i.e., a distinct-strategy, while in about 20%, part of the turning and sitting take place concurrently, i.e., an overlapping-strategy. A prolonged duration of the separation between tasks in the distinct-strategy (D-interval) and a prolonged duration of the overlap interval in overlapping-strategy (O-interval) are related to worse motor symptoms and poorer cognition. In the present study, we evaluated what strategy is employed by patients with Parkinson's disease (PD) when they transition from turning to sitting.

Methods: 96 participants with PD performed turn to sit as part of the Timed Up and Go test, both with and without medications, while wearing a body-fixed sensor. We quantified the turn-to-sit transition and determined which strategy (distinct or overlapping) was employed. We then stratified the cases and used regression models adjusted for age, gender, height, and weight to examine the associations of the D-interval or O-interval with parkinsonian features and cognition.

Results: Most patients (66%) employed the overlapping-strategy, both off and on anti-parkinsonian medications. Longer O-intervals were associated with longer duration of PD, more severe PD motor symptoms, a higher postural-instability-gait-disturbance (PIGD) score, and worse freezing of gait. Longer D-intervals were not associated with disease duration or PD motor symptoms. Neither the D- nor O-intervals were related to cognitive function. Individuals who employed the overlapping-strategy had more severe postural instability (i.e., higher PIGD scores), as compared to those who used the distinct-strategy.

Significance: In contrast to older adults without PD, most patients with PD utilize the overlapping strategy. Poorer postural and gait control are associated with the strategy choice and with the duration of concurrent performance of turning and sitting. Additional work is needed to further explicate the mechanisms underlying these strategies and their clinical implications.

1. Introduction

The ability to turn during ambulation is impaired among patients with Parkinson's disease (PD) [1–7]. These alterations in turning have been related to falls and to freezing of gait (FOG) [1,4,8,9]. Advancing the understanding of turns in PD may, therefore, provide new insights into a common, everyday motor task that is associated with two major adverse outcomes of PD.

Several aspects of turning are altered in PD [1–7]. Patients with PD exhibit poorer balance and impaired segmental coordination while turning during walking, compared to healthy older adults. Although patients with PD use the same top-down sequence of segment reorientation during turning while walking as healthy older adults [10], the timing of the movement of body segments differs in PD. Patients have a shortened delay between the onset of the head and shoulder reorientation and have a longer delay between the pelvis and foot

* Corresponding author at: Center for the Study of Movement, Cognition, and Mobility, Neurological Institute, Aviv Sourasky Medical Center, 6 Weizman Street, Aviv, 64239, Israel.
E-mail address: jhausdor@tlvmc.gov.il (J.M. Hausdorff).

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reorientation. In general, patients with PD approach turns with a slower step and take slower and wider turns, with narrower and increased number of steps, and significantly decreased rotation of the trunk compared to healthy older adults. When patients with PD perform the turns, their head and upper trunk rotation occur almost concurrently instead of in a cranio-caudal sequence as in healthy older adults [10,11]. This concurrent movement is consistent with the clinical description of "turn en bloc".

The successful completion of a specified motor task like a turn to sit depends on the choice and timing among the individual subtasks needed to meet the overall task requirements, as well as on the coordination and movement speed of different body segments. Using a body-fixed sensor, our group and others have extracted additional aspects of mobility tasks like the Timed Up and Go to better appreciate and quantify the heterogeneity of gait impairments among older adults [12–14]. Applying this approach [15], we recently identified two strategies that older adults take when they turn to sit: 1) the *distinct-strategy*, in which turning is first completed and only then sitting begins, and 2) the *overlapping-strategy*, in which part of the turning and sitting take place concurrently, in an overlapping manner. In a study among 1055 community dwelling older adults without PD [15], almost 80% of the subjects used the distinct-strategy and only ~20% employed the overlapping-strategy. Interestingly, a prolonged duration of the separation between tasks in the distinct-strategy (D-interval) and a prolonged duration of the overlapping interval in overlapping-strategy (O-interval) were both related to worse parkinsonian scores and poorer cognitive function among these non-PD older adults.

Since patients with PD perform turns more slowly, take more steps to complete the turn, exhibit bradykinesia and, in general, have problems sequencing motor tasks, one could speculate that they would use the distinct-strategy when turning to sit, like the vast majority of healthy older adults. On the other hand, their delayed segmental coordination and the concurrent, en bloc head and trunk rotation could suggest that they might more often opt for the overlapping-strategy. The primary purpose of the present study was to determine which strategy is employed by adults with PD when transitioning from turning to sitting. In light of the known motor impairments in PD, we speculated, that once a strategy is chosen, a longer D-interval and a longer O-interval would be associated with more severe PD motor symptoms. In addition, similar to what was observed in the older adults, we anticipated that longer D-intervals and longer O-intervals would also be related to cognitive function. Moreover, like certain other aspects of gait, we expected that the strategy employed might change in response to dopaminergic medications.

2. Methods

The study participants, i.e., 96 patients with PD [16], and methods [15,16] have been detailed previously and are summarized briefly below.

2.1. Subjects

Patients were recruited as part of an investigation of white matter changes in PD [16]. The patients were recruited from our databases, referrals from specialists in the outpatient movement disorders unit, and from affiliated clinics. Ethics approval from the Human Research Ethics Committee of Tel Aviv Sourasky Medical Center was given, and all participants provided written informed consent. Briefly, subjects were included if they were diagnosed by a movement disorders specialist with idiopathic PD, were between 40–85 years of age, and were not demented. Subjects were excluded if they had brain surgery or significant comorbidities likely to affect gait, e.g., orthopedic disease, any other neurological diseases, or major depression.

2.2. Timed Up and Go (TUG) protocol

The patients were tested in the OFF medication cycle in the morning (about 12 h after taking their anti-parkinsonian medications). We focused on this state as it allows us to examine associations between turning performance and motor symptoms without the confounding effect of treatment. The TUG was performed twice while wearing a hybrid inertial measurement unit on the lower back. Subjects were instructed to stand up, walk at comfortable pace for a distance of 3 m, turn 180°, walk back to the chair and sit down [17]. The second trial was used in the present analyses [17]. The TUG testing was conducted again after the subjects took their morning, regular dose of anti-parkinsonian medications and after they reported entering the ON medication state (typically 30–60 min after taking the medications). Unless otherwise indicated, all results are reported based on the assessment in the OFF medication state.

2.3. Time Up and Go data collection and measures

Participants wore a small, light-weight sensor (DynaPort Hybrid, McRoberts, the Netherlands) attached to a Velcro elastic belt on their lower back. The dimensions of the unit are 87 × 45 × 14 mm, 74 g. The hybrid device includes a triaxial accelerometer (sensor range and resolution ± 2 g and ± 1 mg, respectively) and a triaxial gyroscope (sensor range and resolution ± 100 and ± 0.0069°/s, respectively). Altogether, six acceleration and angular velocity signals were acquired. Signals include three acceleration axes: (1) vertical acceleration (V), (2) mediolateral acceleration (ML) and (3) anterior–posterior acceleration (AP). The three angular velocity axes were the following: (1) yaw- which is the rotation around the V axis; (2) pitch- which is the rotation around the ML axis; and (3) roll- which is the rotation around the AP axis. Data were saved on a Secure Digital card at a sample frequency of 100 Hz and later transferred to a personal computer for further analysis (using Matlab, the Mathworks software).

The automated algorithm for detecting the start and end times of the instrumented TUG was applied, as previously described [13,18]. As illustrated in Fig. 1, the algorithm also measured the interval between the two subtasks, i.e., the duration between the end of the turn (determined by the yaw axis) and the beginning of the stand to siting subtask (determined by the anterior-posterior axis) [15]. If the distinct-strategy was used, the interval is referred to as the D-interval and the value is positive. If the overlapping-strategy was used, the interval is negative and its absolute value is reported as the O-interval.

2.4. Assessment of Parkinson's disease motor symptoms

Subjects were characterized with respect to disease duration and severity of motor symptoms as quantified using part III of the Unified Parkinson's Disease Rating, MDS-UPDRS [19] in the OFF medication condition. Individual components of the UPDRS items were summed to generate a tremor score and a postural instability and gait difficulty (PIGD) score [16]. The new Freezing of Gait questionnaire (FOG-Q) was used to evaluate freezing of gait severity [20], a motor symptom that is common among patients with more advanced disease.

2.5. Assessment of cognitive function and depressive symptoms

The cognitive assessment, which was conducted in the ON medication state, included the Mini Mental State Exam (MMSE) [21] and the Montreal Cognitive Assessment (MoCA) [22]. Subjects also completed a computerized cognitive battery (Mindstreams®, NeuroTrax Corp., NJ) that evaluated several domains including attention, executive function, memory and a global cognitive score (GCS) [23]. The battery incorporated computerized versions of the Go-No-Go and the Stroop interference tests. The test battery generates composite indices of each domain on an IQ-like scale, with 100 representing the estimated

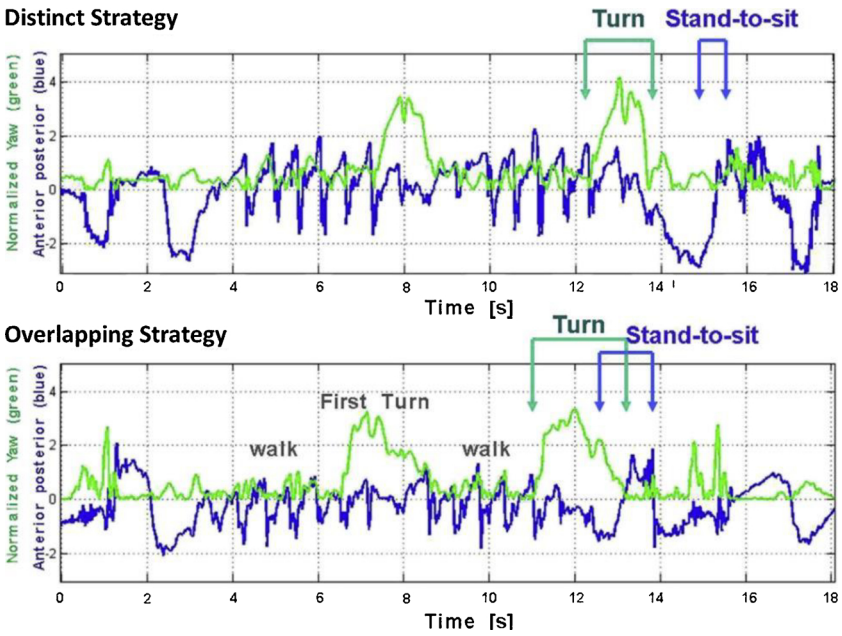

Fig. 1. Examples of the two turn-to-sit strategies are illustrated here: (above) distinct strategy and (below) overlapping strategy. The start and end times of the turn and the stand to sit were derived from the normalized yaw (green) and anterior-posterior (blue) axes, respectively. In the distinct-strategy example, the turn is completed (green) before the initiation of the stand to sit movement (blue).The lower figure shows the TUG yaw and anterior-posterior signal of an overlapping strategy The turn is completed (green) after the initiation of the stand to sit movement (blue). Adapted from Weiss et al. [15] (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

population mean normalized for age and education and 15 represents 1 SD. This battery was previously validated in patients with PD [24–26].

2.6. Statistical analyses

We examined the associations between the D-interval and the O-interval and PD symptoms (and other measures) using linear regression models (enter method, with the D-interval or the O-interval as the dependent variable, adjusted for age, gender, height, weight). Standardized beta values and corresponding p-values are reported for the regression analyses. When comparing the subject characteristics of those who used the D-interval to those who used the O-interval, we used Student's t-tests for continuous variables (e.g., age, height) and Chi-square tests for categorical measures (i.e., gender). Subsequently, we compared group differences in PD severity and other measures (e.g., UPDRS motor scores, Timed Up and Go times) of those who selected the distinct versus overlapping strategy using ANCOVA that allowed us to adjust for potential covariates (e.g., age, gender, height, weight). Group summaries are reported as adjusted mean ± standard error. Statistical analyses were carried out using SPSS version 22.

3. Results

The cohort (n = 96) was comprised of 22% female with a mean age of 64.03 ± 9.03 yrs (Table 1). The mean disease duration was 5.37 ± 3.45 yrs, and the mean MDS-UPDRS motor score at "OFF" was 39.79 ± 13.11 points. On average, the subjects completed the Timed Up and Go in 10.02 ± 2.36 s in the OFF medication state and 9.49 ± 2.14 s in the ON medication state.

During OFF medication testing, about two-thirds of the participants (65.4%, n = 63) performed the turn using the overlapping-strategy while a minority of the participants (34.6%, n = 33) performed the turn using the distinct-strategy. Among subjects who used the distinct-strategy, the average D-interval was 380.0 ± 737.4 msec. Among those subjects who used the overlapping-strategy, the average O-interval was 365.4 ± 249.9 ms.

3.1. Correlates of distinct transition strategy (distinct-strategy) duration (D-interval)

Table 2 summarizes the associations between the D-interval and disease duration and motor severity. In models that adjusted for age, gender, height and weight, there were no significant associations with the D-interval. The D-interval was not correlated with any of the cognitive measures ($p > 0.15$).

3.2. Clinical correlates overlapping transition strategy (overlapping-strategy) duration (O-interval)

Table 2 also summarizes the associations between the O-interval and disease duration and motor severity. In the models that adjusted for age, gender, height and weight, five measures were significantly associated with the O-interval. Subjects who had longer O-intervals had more years of disease duration, higher (i.e., poorer) scores on the UPDRS motor part, higher (more severe) rigidity scores, higher (worse) postural instability gait difficulty (PIGD) scores, and more severe freezing of gait. In models that also adjusted for disease duration, the PIGD score was still significantly associated with the O-interval. Further, in stepwise regression models that included the UPDRS motor scores, the new FOG questionnaire score, and the PIGD score, only the PIGD score remained significantly associated with the O-interval (with or without the inclusion of disease duration). The O-interval was not correlated with any of the cognitive measures ($p > 0.15$).

3.3. Distinct versus overlapping strategy patients

Participants who employed the overlapping-strategy were taller and included a smaller percentage of women; age, weight, body-mass-index, and years of education were similar among the subjects who selected the distinct-strategy and those who selected the overlapping-strategy (Table 1, right columns).

When taking into account demographic features, participants who used the overlapping-strategy had worse ($p = 0.024$) PIGD scores (4.80 ± 0.34), compared to those who used the distinct-strategy (3.39 ± 0.48). Time to complete the Timed Up and Go was similar in the two groups (Distinct-strategy: 9.97 ± 0.43 s; Overlapping-strategy: 9.68 ± 0.29 s; $p = 0.579$). All other measures of disease duration, severity, and cognitive function (see Table 3) were also similar ($p > 0.15$) in the distinct-strategy and the overlapping-strategy groups.

Table 1
Subject characteristics of the study participants and when stratifying the participants into those who used the distinct and overlapping strategies.

	All Participants	Distinct Strategy Patients	Overlapping Strategy Patients	p-value[a]
# of subjects (N)	96	33	63	
Age (yrs)	64.12 ± 9.05	63.88 ± 8.60	64.25 ± 9.35	0.850
Gender (% women)	22%	36%	16%	**0.023**
Height (m)	1.70 ± 0.84	1.66 ± 0.73	1.72 ± 0.08	**0.001**
Weight (kg)	78.30 ± 11.97	76.03 ± 12.11	79.50 ± 11.82	0.260
Body-mass-index (kg/m2)	26.99 ± 3.46	27.51 ± 3.92	26.72 ± 3.20	0.355
Years of education (yrs)	15.64 ± 3.81	15.21 ± 3.22	15.86 ± 4.10	0.546
Timed Up and Go test features[b]				
	All Participants	Distinct Strategy Patients	Overlapping Strategy Patients	p-value
Total task duration ON (sec)	9.74 ± 0.23	9.97 ± 0.43	9.68 ± 0.29	0.579
Turn duration ON (sec)	1.88 ± 0.05	1.82 ± 0.09	1.91 ± 0.06	0.410
Stand to sitting duration ON (sec)	0.79 ± 0.05	0.71 ± 0.10	0.84 ± 0.07	0.285
Total task duration OFF (sec)	10.08 ± 0.22	10.30 ± 0.40	9.89 ± 0.28	0.418
Turn duration OFF (sec)	1.97 ± 0.05	1.77 ± 0.08	2.05 ± 0.06	**0.008**
Stand to sitting duration OFF (sec)	0.82 ± 0.06	0.66 ± 0.10	0.88 ± 0.07	0.074

[a] Comparing Distinct-strategy to Overlapping-strategy patients.
[b] Comparison between Distinct-strategy to Overlapping-strategy patients was adjusted to age, gender, height and weight using Univariate ANOVA. Values are presented as adjusted means ± standard error.

Table 2
Associations between D-interval and O-interval transition durations and PD features in the two sub-groups.

	D-interval Among patients who used the Distinct Strategy (β, p-value)[a]	O-interval Among patients who used Overlapping Strategy (β, p-value)[a]
Disease duration	−0.223, 0.237	0.244, **0.035**
UPDRS motor scores (part III)	−0.776, 0.445	0.273, **0.019**
Bradykinesia score	−0.144, 0.465	0.201, 0.089
Rigidity score	0.022, 0.922	0.240, **0.044**
Postural instability gait difficulty score	−0.247, 0.243	0.332, **0.008**
Tremor score	0.020, 0.993	−0.100, 0.930
Freezing of Gait-Q score	−0.268, 0.150	0.265, **0.026**

[a] Regression models adjusted to age, gender, height and weight. P-values that are significant are bolded.

Table 3
Cognitive function and depressive symptoms in patients who selected the distinct and overlapping strategies.

	Distinct Strategy (n = 33)	Overlapping Strategy (n = 63)	p-value
Mini Mental Status Examination	29.06 ± 0.27	28.75 ± 0.19	0.358
Montreal Cognitive Assessment	25.11 ± 0.57	25.63 ± 0.41	0.480
Global Cognitive Score	95.17 ± 2.19	94.41 ± 1.55	0.785
Memory	99.03 ± 2.81	96.20 ± 1.99	0.427
Executive function	95.28 ± 2.47	95.41 ± 1.75	0.966
Attention	95.86 ± 2.91	94.83 ± 2.06	0.781
Geriatric Depression Scale	3.66 ± 0.61	4.35 ± 0.44	0.372

3.4. Anti-parkinsonian medication effect

Similar to what was observed in the OFF medication condition, more subjects selected the overlapping strategy in the ON medication condition (66% used the overlapping-strategy and 34% used the distinct-strategy). A within-subject analysis revealed that 73% of the subjects maintained the same strategy during both ON and OFF medication state, which was significantly different from chance ($p < 0.001$). Medication effect on strategy selection was observed in 27% of the subjects; 14% changed from overlapping to distinct strategy during ON condition and 13% changed from the distinct to overlapping strategy after medication intake.

4. Discussion

Patients with PD were almost twice as likely to choose the overlapping strategy (66%) as the distinct strategy (34%). Interestingly, the selection of the strategy was apparently not related to dopaminergic processes as the percentage of subjects who used each strategy was similar both off and on anti-parkinsonian medications. Once a strategy was selected, the associations between PD symptoms, on the one hand, and the D-interval and the O-interval, on the other, were different.

The present findings are, to some degree, the opposite of what was previously observed among older adults without PD (see Fig. 2). In that previous work, about 80% older adults chose the distinct strategy [15], while in the present study, most PD patients used the overlapping strategy (Fig. 2). The non-PD cohort (mean age 80 yrs; 73% women) was older and was predominantly women relative to the current PD cohort. Still, even after adjusting for age and gender, the group differences persisted ($p < 0.001$). Similar to what was observed in older adults, among those who used an overlapping strategy, longer O-

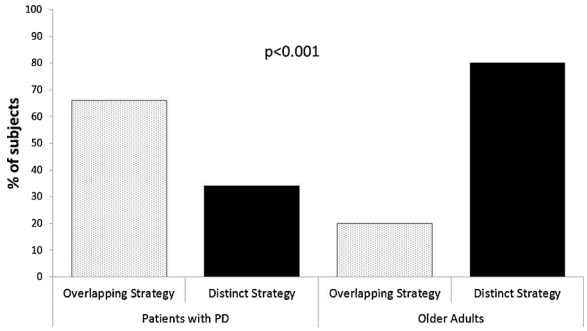

Fig. 2. Comparison of the percentage of PD subjects who chose each strategy (based on the present study) to the percentage of older adults who chose each strategy (based on Weiss et al. [15]). While older adults chose the distinct strategy, most patients with PD chose the overlapping strategy ($p < 0.001$). Similar group differences were observed if we selected an age and gender matched sub-group of the older adults and controlled for age and gender in a logistic regression model.

intervals tended to be associated with worse PD signs, in particular, worse PIGD score as well as with rigidity, with a tendency towards an association with bradykinesia. However, in contrast to what was seen among the non-PD older adults, we found no associations with the D-interval and PD symptoms. Based on these two studies, one can suggest that the use of the overlapping-strategy is related to poorer balance and gait. Nonetheless, it is still not fully clear why the PD subjects were more likely to use the overlapping strategy.

Previous studies observed that patients with PD have impaired segmental coordination when asked to perform a 90° turn [10,27]. While healthy older adults first performed a sequential head rotation followed by an upper trunk rotation and a pelvis rotation toward the direction of movement, patients with PD rotated the head and upper trunk almost concurrently followed by the pelvis rotation. Although the specifics of the turn type differ in earlier reports and the present study, in some ways, those findings are parallel to the present findings. As suggested by the results in Tables 2, this lack of segmentation may be related to poorer balance control. In other words, the ability to separate between the two motor tasks of turning and sitting might be more difficult and require better muscle and equilibrium control. Therefore, performing these two movements concurrently might be easier for those patients and, therefore, result in the overlapping strategy.

. In addition, patients with PD have delayed segmental coordination, as well as reduced rotation magnitude in multiple body segments compared to healthy older adults [5–7,10,27,28]. This may also explain in part why the patients with PD perform the turning and sitting movements concurrently when turning to sit, instead of first completing their turning and only then performing the sitting movement. Less variation and lower magnitude of the rotation of different body segments along with troubles in sequencing may reflect less control and less ability to separate the turning movement from the sitting movement which follows, and hence this may have led to a higher prevalence of the overlapping-strategy. This strategy may also be a reflection of the 'free-fall" nature that frequently occurs when a person with PD attempts to sit from the standing position or while turning [6]. Patients with PD find it difficult to decelerate during the phase of the Stand-to-Sit task i.e., an impaired ability to generate eccentric muscle contractions in pelvic and lower extremities [6].

While questions remain about what contributes to the use of the overlapping strategy in PD, the present findings help us to exclude two potential mechanisms. PD is generally accompanied by mild cognitive deficits, particularly, attention and executive function [29]. Indeed, while Mini Mental Status Examination Scores of the patients with PD in the present study were near perfect (Table 3), mean scores of attention and executive function indices were below the age- and education-normed values of 100.0 (recall Table 3). Still, multiple measures of cognitive function were not related to the choice of strategy and were not related to the duration of the D-intervals or the O-intervals. Cognitive function, e.g., cholinergic dysfunction which has been associated with cognitive deficits in PD, apparently can be ruled out as playing a key role in the present findings. Similarly, the current results show that a similar percentage of subjects choose the overlapping strategy in the off and on medication states, suggesting that dopaminergic pathways are not likely a major contributor to the choice of strategy. This lack of responsiveness of the turning characteristic is similar to what was previously reported for other types of turns and turning features [10]. In addition to dopaminergic and cholinergic systems, other neural transmitters and multiple pathways are affected by PD [30]. By way of exclusion, one can speculate that perhaps these other factors play a role in the selection of the strategy choice. Of course, the observed behavior may reflect impairment due to multiple networks and neurotransmitters and is not likely caused by alterations of a single neurotransmitter.

The present study has several limitations. The cross sectional nature of the findings limit the ability to evaluate cause and effect and do not allow us to estimate if or how alterations in turning strategy and turning intervals change over time with disease progression and in response to non-dopaminergic based interventions. Direct comparison to a healthy matched control group is also lacking and it could be that some unknown, subtle changes in the methods (e.g., different assessors) contributed to the differences observed between the PD and healthy control groups. Further, while there is some suggestion for the underlying mechanism (i.e., poor balance and motor control), we do not yet have a full explanation for the somewhat surprising choice of strategy taken by most individuals with PD. A recent review posited that turning deficits in PD can be divided into axial (i.e., altered segment co-ordination, turn en bloc) and perpendicular (e.g., shorter and more steps) and that the latter may drive the former [1]. Perhaps this contributed to the turning strategy. Motivated by the present findings, future work should more fully address these questions and if and how turning strategy and features can be used to monitor certain aspects of PD. In the meantime, the present findings indicate that the strategy and sequence taken by patients with PD as they transition from walking, to turning, and to a sitting position is not as exactly expected. In addition, it appears that the identification of the strategy is reliable in patients with moderate to advanced PD and that the choice of this strategy is generally not influenced by anti-parkinsonian medications. Further, the present findings join a growing body of literature which illustrates the added value of using body-fixed sensors to carefully assess movement patterns in older adults and patients with neurological impairment. Future work is needed to determine the basis for the strategy choice in PD, to more fully explicate the factors that contribute to the duration of the sequencing of turning and sitting motor tasks, and to evaluate the potential clinical utility of these measures.

Conflictof interest statement

None.

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References

[1] S. Hulbert, A. Ashburn, L. Robert, G. Verheyden, A narrative review of turning deficits in people with Parkinson's disease, Disabil. Rehabil. 37 (15) (2015) 1382–1389.
[2] K. Lebel, H. Nguyen, C. Duval, R. Plamondon, P. Boissy, Capturing the cranio-caudal signature of a turn with inertial measurement systems: methods, parameters robustness and reliability, Front. Bioeng. Biotechnol. 5 (2017) 51.
[3] K. Lebel, C. Duval, H.P. Nguyen, R. Plamondon, P. Boissy, Cranio-caudal kinematic turn signature assessed with inertial systems as a marker of mobility deficits in Parkinson's disease, Front. Neurol. 9 (2018) 22.
[4] M. Mancini, K. Smulders, R.G. Cohen, F.B. Horak, N. Giladi, J.G. Nutt, The clinical significance of freezing while turning in Parkinson's disease, Neuroscience 343 (2017) 222–228.
[5] J.M. Van Uem, S. Walgaard, E. Ainsworth, et al., Quantitative timed-up-and-Go parameters in relation to cognitive parameters and health-related quality of life in mild-to-Moderate parkinson's disease, PLoS One 11 (4) (2016) e0151997.
[6] A. Weiss, T. Herman, M. Plotnik, et al., Can an accelerometer enhance the utility of the Timed Up & Go test when evaluating patients with Parkinson's disease? Med. Eng. Phys. 32 (2) (2010) 119–125.
[7] C. Zampieri, A. Salarian, P. Carlson-Kuhta, K. Aminian, J.G. Nutt, F.B. Horak, The instrumented timed up and go test: potential outcome measure for disease modifying therapies in Parkinson's disease, J. Neurol. Neurosurg. Psychiatry 81 (2) (2010) 171–176.
[8] B.R. Bloem, J.M. Hausdorff, J.E. Visser, N. Giladi, Falls and freezing of gait in Parkinson's disease: a review of two interconnected, episodic phenomena, Mov. Disord. 19 (8) (2004) 871–884.
[9] M. Mancini, A. Weiss, T. Herman, J.M. Hausdorff, Turn around freezing: community-living turning behavior in people with Parkinson's disease, Front. Neurol. 9 (2018) 18.
[10] S. Akram, J.S. Frank, M. Jog, Parkinson's disease and segmental coordination

during turning: II. Walking turns, Can. J. Neurol. Sci. 40 (4) (2013) 520–526.
[11] S.B. Akram, J.S. Frank, S. Chenouri, Turning behavior in healthy older adults: is there a preference for step versus spin turns? Gait Posture 31 (1) (2010) 23–26.
[12] A. Salarian, F.B. Horak, C. Zampieri, P. Carlson-Kuhta, J.G. Nutt, Aminian K. iTUG, A sensitive and reliable measure of mobility, IEEE Trans. Neural Syst. Rehabil. Eng. 18 (3) (2010) 303–310.
[13] A. Weiss, T. Herman, M. Plotnik, M. Brozgol, N. Giladi, J.M. Hausdorff, An instrumented timed up and go: the added value of an accelerometer for identifying fall risk in idiopathic fallers, Physiol. Meas. 32 (12) (2011) 2003–2018.
[14] A. Mirelman, A. Weiss, A.S. Buchman, D.A. Bennett, N. Giladi, J.M. Hausdorff, Association between performance on timed up and go subtasks and mild cognitive impairment: further insights into the links between cognitive and motor function, J. Am. Geriatr. Soc. 62 (4) (2014) 673–678.
[15] A. Weiss, A. Mirelman, N. Giladi, et al., Transition between the timed up and go turn to sit subtasks: is timing everything? J. Am. Med. Dir. Assoc. 17 (9) (2016) 864.
[16] T. Herman, K. Rosenberg-Katz, Y. Jacob, et al., White matter hyperintensities in Parkinson's disease: do they explain the disparity between the postural instability gait difficulty and tremor dominant subtypes? PLoS One 8 (1) (2013) e55193.
[17] D. Podsiadlo, S. Richardson, The timed "Up & Go": a test of basic functional mobility for frail elderly persons, J. Am. Geriatr. Soc. 39 (2) (1991) 142–148.
[18] A. Weiss, A. Mirelman, A.S. Buchman, D.A. Bennett, J.M. Hausdorff, Using a body-fixed sensor to identify subclinical gait difficulties in older adults with IADL disability: maximizing the output of the timed up and go, PLoS One 8 (7) (2013) e68885.
[19] C.G. Goetz, B.C. Tilley, S.R. Shaftman, et al., Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS): scale presentation and clinimetric testing results, Mov. Disord. 23 (15) (2008) 2129–2170.
[20] A. Nieuwboer, L. Rochester, T. Herman, et al., Reliability of the new freezing of gait questionnaire: agreement between patients with Parkinson's disease and their carers, Gait Posture 30 (4) (2009) 459–463.
[21] M.F. Folstein, S.E. Folstein, P.R. McHugh, "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician, J. Psychiatr. Res. 12 (3) (1975) 189–198.
[22] Z.S. Nasreddine, N.A. Phillips, V. Bedirian, et al., The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment, J. Am. Geriatr. Soc. 53 (4) (2005) 695–699.
[23] T. Dwolatzky, V. Whitehead, G.M. Doniger, et al., Validity of a novel computerized cognitive battery for mild cognitive impairment, BMC Geriatr. 3 (1) (2003) 4.
[24] E. Auriel, J.M. Hausdorff, T. Herman, E.S. Simon, N. Giladi, Effects of methylphenidate on cognitive function and gait in patients with Parkinson's disease: a pilot study, Clin. Neuropharmacol. 29 (1) (2006) 15–17.
[25] G. Yogev, N. Giladi, C. Peretz, S. Springer, E.S. Simon, J.M. Hausdorff, Dual tasking, gait rhythmicity, and Parkinson's disease: which aspects of gait are attention demanding? Eur. J. Neurosci. 22 (5) (2005) 1248–1256.
[26] A. Weiss, T. Herman, N. Giladi, J.M. Hausdorff, Association between community ambulation walking patterns and cognitive function in patients with Parkinson's disease: further insights into motor-cognitive links, Parkinsons Dis. 2015 (2015) 547065.
[27] S. Akram, J.S. Frank, M. Jog, Parkinson's disease and segmental coordination during turning: I. Standing turns, Can. J. Neurol. Sci. 40 (4) (2013) 512–519.
[28] A. Salarian, C. Zampieri, F.B. Horak, P. Carlson-Kuhta, J.G. Nutt, K. Aminian, Analyzing 180 degrees turns using an inertial system reveals early signs of progression of Parkinson's disease, Conf. Proc. IEEE Eng. Med. Biol. Soc. 2009 (2009) 224–227.
[29] D. Aarsland, B. Creese, M. Politis, et al., Cognitive decline in Parkinson disease, Nat. Rev. Neurol. 13 (4) (2017) 217–231.
[30] A.H.V. Schapira, K.R. Chaudhuri, P. Jenner, Non-motor features of Parkinson disease, Nat. Rev. Neurosci. 18 (7) (2017) 435–450.