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BRIEF COMMUNICATION

Spatiotemporal Gait Parameters During Turning and Imbalance in Parkinson's Disease: Video-Based Analysis From a Single Camera

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ABSTRACT

Objective This study aims to objectively evaluate turning gait parameters in Parkinson's disease (PD) patients using 2D-RGB video-based analysis and explore their relationships with imbalance.

Methods We prospectively enrolled PD patients for clinical assessment, balance analysis and gait with 180° turning. Spatiotemporal gait parameters during turning were derived using video-based analysis and correlated with modified Hoehn and Yahr (mHY) stages and center of pressure (COP) oscillations.

Results A total of 64 PD patients were enrolled. The PD patients with higher mHY stages (≥2.5) had significantly longer turning times, greater numbers of steps, wider step bases and less variability in step length during turns. COP oscillations were positively correlated with the mean turning time on both the anterior-posterior and right-left axes.

Conclusion Spatiotemporal gait parameter during turning, derived from video-based gait analysis, may represent apromising biomarker for monitoring postural instability in PD patients.

Keywords Parkinson's disease; Gait; Turning; Postural instability; Video-based analysis.

INTRODUCTION

Falls are common in people with Parkinson's disease (PD), with an average of 60% of PD patients reporting at least one fall and 39% reporting recurrent falls.[1] Falls are a significant cause of disability, loss of independence and reduced quality of life in people with PD.[2] Thus, it is crucial to predict and monitor falls in the PD population. In the objective evaluation of postural instability, center of pressure (COP) oscillations measured while standing on a force plate are increased in patients with PD compared with controls and are associated with postural instability and falls.[3,4] During gait, the turning phase stands out as a critical point where PD patients are particularly prone to falls, and more than half of individuals with PD struggle with turning, significantly increasing their risk of falls.[5] Previous studies utilizing objective instrumental tools have demonstrated that turning gait parameters in PD patients are impaired in both spatial and temporal dimensions and are associated with falls and freezing of gait

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(FOG).[6,7] These features significantly differentiated PD patients from controls even in the early stage.[8,9] Therefore, conducting an objective assessment of spatiotemporal gait patterns during turning is imperative for understanding the underlying pathophysiology and predicting postural instability and falls in PD patients. However, conventional gait analysis tools widely used for PD, such as pressure mats or treadmill systems, lack the ability to provide assessments during turning. This study aimed to demonstrate that turning gait parameters can be effectively derived from single RGB videos using video-based analysis and that these parameters reflect both clinical postural instability and COP oscillations in PD patients.

MATERIALS & METHODS

Patient inclusion

In this study, we prospectively enrolled PD patients at the Seoul National University Hospital outpatient clinic from March 2022 to February 2024. PD patients were diagnosed based on clinical criteria,[10] and those who could not walk without assistance were excluded. Furthermore, we excluded PD patients with significant musculoskeletal conditions or spinal disorders, including spinal stenosis and radiculopathy, that could affect gait. We systematically collected demographic variables, including age, sex, disease duration, and levodopa equivalent daily dose (LEDD), and evaluated them using the Movement Disorder Society-Unified Parkinson's Disease Rating Scale (MDS-UPDRS).

Patient evaluation

After signing the informed consent, the participants were given specific instructions to walk a 7-meter walkway, performing a sequence of gaits that included walking forward, turning 180 degrees, and walking back. This sequence was repeated more than 5 times to ensure a robust dataset. The entire task was video recorded with a single RGB camera (60 Hz, Galaxynote 7, Samsung, Suwon, Korea) with a frontal view, and videos were analyzed using a previously established 3D video-based gait analysis system referred to as the gaitome (Figure 1A).[11,12] The turning phase during these movements was precisely estimated using measurements of shoulder distance and acceleration (Figure 1A). We derived the time required for turning, the mean number of steps during turning, the step length, the step base and the velocity during the turning phase on the basis of algorithms that were previously described (Figure 1B-D).[11,12] Step length was defined as the distance between the left and right feet during their stance phases, whereas the step base length was defined as the perpendicular distance between one foot and the trajectory of the other foot (Figure 1C and D). The turning velocity was calculated as the total step length divided by the time spent for the corresponding steps. Step length/base variability was calculated as the coefficient of variation, defined as [(standard deviation/mean)×100] for step length/base. Additionally, we conducted a balance analysis using the PedoScan system (DIERS International, Wiesbaden, Germany). COP oscillations were measured as the length of the COP trace over time using a 0.5 m×0.5 m force plate with a 120 Hz sampling rate, processed through the built-in software of the Pedoscan system. This analysis involved calculating the average COP oscillations along the anterior-posterior (AP) and right-left (RL) axes as participants stood in a neutral position for 10 seconds. All the clinical evaluations, gait assessments, and balance analyses were performed while the participants were in a medication-on state.

Video-based gait analysis and statistical analysis

The correlations between turning gait parameters and clinical parameters and COP oscillation in the PD population were determined using Spearman's partial correlation analysis, with age, sex and LEDD as cofactors. The comparison between turning gait parameters and COP oscillations between the low-modified Hoehn and Yahr (mHY) group and the high-mHY group was performed with generalized linear model regression analysis adjusted for age, sex and LEDD. The Institutional Review Board of Seoul National University Hospital approved this study (1908-175-1059).

RESULTS

Patient characteristics

We enrolled 64 PD patients (23 males and 41 females) who underwent clinical assessment, video-based gait analysis, and balance analysis. The mean age was 68.35±9.34 years, and the disease duration was 4.79±4.98 years. Supplementary Table 1 (in the online-only Data Supplement) details their clinical characteristics, turning gait parameters, and COP oscillations. Turning time was positively correlated with age, while step length and turning velocity were negatively correlated with age (Supplementary Table 2 in the online-only Data Supplement). The number of steps and the variability in step number during turning showed positive correlations with disease duration, and step base during turning was positively correlated with LEDD (Supplementary Table 2 in the online-only Data Supplement). No significant differences in turning parameters were observed between sexes ($p>0.05$) (Supplementary Table 2 in the online-only Data Supplement).

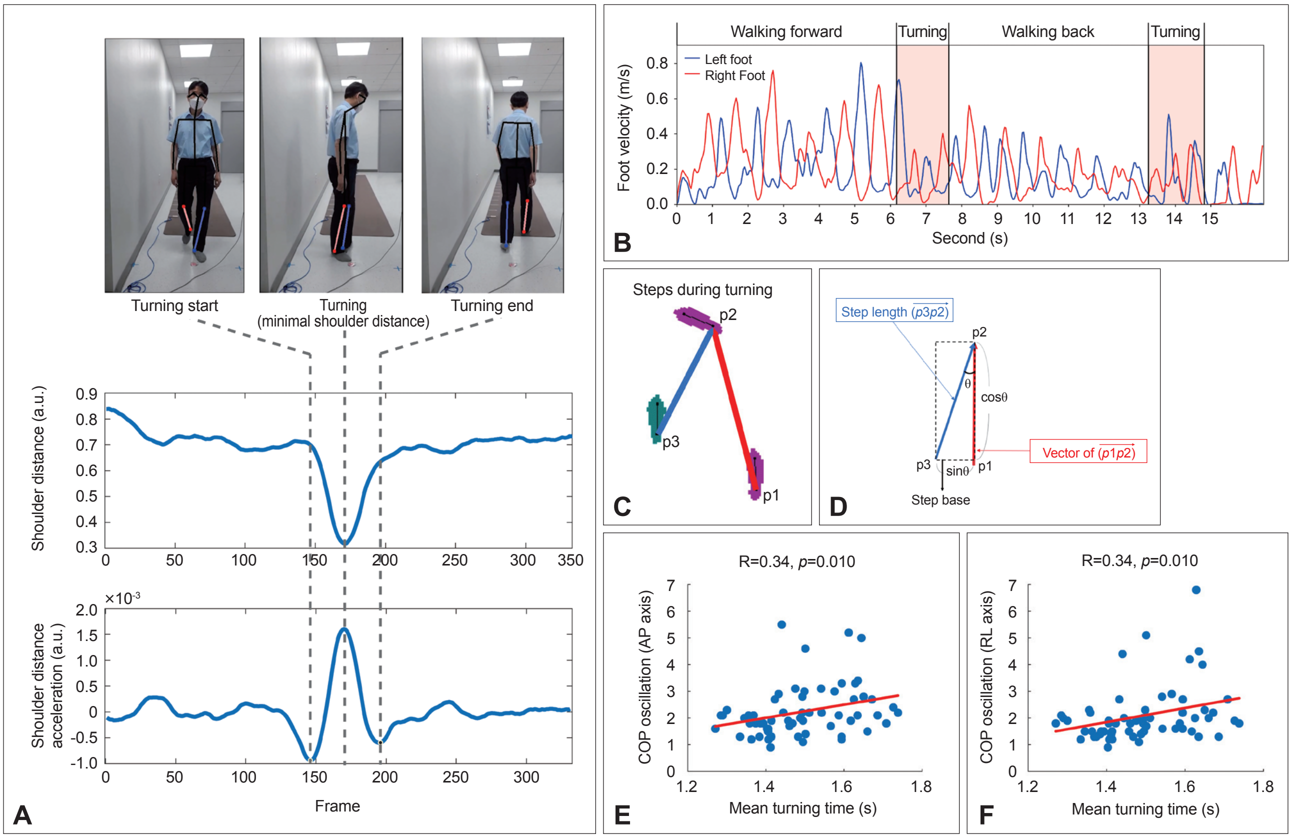

Figure 1. Video-based turning analysis. A: Schematic drawing of turning phase detection. The distances between the shoulders were traced using the pose estimation algorithm previously described. The negative peak acceleration of the shoulder distance adjacent to the timing of turning (minimal shoulder distance) was chosen as the turning start and turning end. B: Velocity traces of the left and right feet while walking forward, turning and walking back. The turning phase is shaded in light red. C: Example step trajectory during turning. Here, p1 and p2 represent the right foot trace, and p3 represents the left foot trace during turning. D: With the vectors $\overline{p3p2}$ and $\overline{p1p2}$, we derive an angle between these two vectors (θ). The step base was derived as the sine (θ) value of the step length (size of the vector). E and F: Correlations between mean turning time and COP oscillation in the AP axis (E) and RL axis (F). a.u., arbitrary unit; COP, center of pressure; AP, anteroposterior; RL, right-left.

Turning gait parameters and imbalance

First, we evaluated the relationships between turning gait parameters and postural instability. PD patients were divided into two groups based on mHY stages, including low mHY (stages 1 or 2, n=39) and high mHY (stages 2.5 to 4, n=25), with the clinical characteristics summarized in Table 1. The high-mHY group had a significantly longer disease duration with worse scores on MDS-UPDRS Parts II and III (Table 1).

The high mHY group presented significantly longer turning times, a greater number of steps for turning, a wider step base, and low variability in step length during turning (adjusted $p<0.05$) (Table 1). A tendency for shorter step lengths was noted in the high mHY group (Table 1). The mean COP oscillations were significantly higher in the high mHY group than in the low mHY group, both in the AP and RL axes (adjusted $p=2.98\times10^{-3}$ for the AP axis; $p=3.26\times10^{-3}$ for the RL axis) (Table 1).

We subsequently explored the relationships between turning gait parameters and COP oscillations. The mean turning time was positively correlated with COP oscillations on both the AP and RL axes (Figure 1E and F). The step base during turning exhibited a positive correlation with COP oscillation along the AP axis, and the number of steps for turning also showed a positive correlation with COP oscillation along the RL axis (Supplementary Table 3 in the online-only Data Supplement).

DISCUSSION

In this study, we revealed a significant correlation between turning gait parameters and both the mHY stage and COP oscillations, suggesting that turning gait parameters derived from video studies may reflect postural instability in PD patients.

In terms of temporal gait parameters, the significant associations of longer turning times with postural instability and COP oscillations (Table 1 and Supplementary Table 3 in the online-only Data Supplement) align with previous studies utilizing iner-

Table 1. Comparison of turning gait parameters and COP oscillations between the low mHY and high mHY groups

Variable	Low mHY (1 or 2)	High mHY (2.5, 3 or 4)	*p* value
Age (yr)	67.15±8.64	71.00±8.41	0.12
Sex, male/female	13/26	10/15	0.68
Disease duration (yr)	3.08±2.49	7.30±7.06	2.50×10^{-3}
MDS-UPDRS Part I	5.69±1.96	4.70±2.75	0.02
MDS-UPDRS Part II	4.10±2.12	9.17±4.24	3.25×10^{-6}
MDS-UPDRS Part III	22.39±10.82	36.06±5.12	5.52×10^{-5}
LEDD (mg/day)	357.72±454.80	495.00±488.96	0.30
Turning gait parameters			
Time required for turning (s)	1.45±0.12	1.56±0.12	0.01
Variability of mean turning time	0.20±0.09	0.21±0.09	0.44
Number of steps for turning	3.02±0.21	3.23±0.29	0.01
Variability of number of steps for turning	0.39±0.06	0.39±0.08	0.89
Step base during turning (m)	0.08±0.02	0.10±0.02	0.03
Variability of step base during turning	0.67±0.15	0.72±0.15	0.22
Step length during turning (m)	0.26±0.07	0.21±0.09	0.07
Variability of step length during turning	0.66±0.10	0.56±0.09	3.54×10^{-4}
Turning velocity (m/s)	0.40±0.12	0.34±0.07	0.24
COP oscillation			
Mean COP oscillation (AP axis, cm)	1.87±0.58	2.84±1.19	2.98×10^{-3}
Mean COP oscillation (RL axis, cm)	1.77±0.51	2.76±1.59	3.26×10^{-3}

All the scores are shown as the means±standard deviations or as numbers only. Comparisons of baseline demographic and clinical parameters were performed using *t*-tests. Generalized linear model regression analysis adjusted for age, sex and the MDS-UPDRS-3 score was used to compare turning gait parameters and COP oscillations between groups.
mHY, modified Hoehn and Yahr; COP, center of pressure; MDS-UPDRS, Movement Disorder Society-Unified Parkinson's Disease Rating Scale; LEDD, levodopa equivalent daily dose; AP, anteroposterior; RL, right-left; s, second; m, meter; m/s, meter/second.

tia monitoring unit (IMU) sensors, demonstrating that slower turning significantly correlates with falls in PD patients.[7]

Associations between spatial gait parameters during turning and freezing or postural instability have been limited by inconsistency and an insufficient number of studies, likely stemming from varied turning strategies among individuals and disparate measurement methods.[13] Despite these challenges, we identified significant correlations within our experimental setting between spatial turning gait parameters and clinical postural instability and COP oscillation.

Unexpectedly, the low mHY group presented significantly higher step length variability than the high mHY group, as shown in Table 1. Notably, 180-degree turning involves a sequence of deceleration and acceleration. Specifically, the step length before entering the turning phase was significantly longer in the low HY group by 7 cm (37.07±4.70 cm vs. 30.20±6.35 cm) in our data. Therefore, the increased step length variability in the low HY group may be attributed to the larger amplitude of deceleration and acceleration during this maneuver.

Studies have analyzed parkinsonian gait using videos; however, most have focused on the lateral (sagittal) view, making it difficult to assess turning gait parameters.[14] Current widely used pressure mat systems and IMU-based studies also have limitations in deriving comprehensive spatiotemporal gait parameters during turning. In contrast, the algorithm used in this study (gaitome)[11,12] has the advantage of analyzing turning gait parameters using the front view of the gait video, which fully captures the entire turning process (Figure 1).

Currently, the importance of continuous real-world monitoring of PD patients is widely recognized based on studies showing that real-world gait, particularly turning, may serve as a sensitive biomarker for PD.[9] Among various strategies, including IMUs or smartphone applications, video-based monitoring stands out for its ability to comprehensively capture motor symptoms in PD, including tremor, bradykinesia, gait, and posture, using a single 2D video.[11,12,15] Owing to recent advancements in computer vision techniques, video-based analysis enables objective and robust analysis without the need for markers or attached devices, and it is readily accessible owing to the widespread distribution of smartphones. Considering our demonstration of the feasibility of objectively deriving turning gait parameters from video-based analysis, we believe that this approach could be applied to other movement disorders, including parkinsonian syndromes, ataxia, and dystonia, where the physiological characteristics of postural instability differ significantly from those of PD.

The limitations of this study include a relatively small sample size consisting of both early- and advanced-stage PD patients, which warrants caution with the generalization of these findings. Gait and turning were evaluated in an observed environment, which may not fully reflect the ecological turning in PD patients and may differ significantly from monitored conditions.[7,16,17] We did not assess gait disturbances in the medication-off state; however, previous studies have shown impairments in turning gait parameters in the off state.[7] The temporal parameters, including single or double support times, were not derived from the gaitome algorithm. The clinical evaluation of falls in PD patients was not performed, so our results cannot be directly related to actual falls in PD patients. The correlation between turning gait parameters and COP oscillations was relatively weak. The application of video-based analysis has not been validated in general settings, particularly with different camera angles. Finally, no clinically significant FOG was observed in the video analysis of any PD patients who participated in this study; however, five patients scored 1 on the MDS-UPDRS Part II FOG subscore. Although FOG can adversely affect turning-related gait parameters, such as turning duration, cadence, step count, and turning velocity,[13] these aspects were not comprehensively analyzed in this study.

In conclusion, turning gait parameters extracted from single 2D RGB videos were significantly correlated with postural instability in PD patients. These findings suggest that spatiotemporal gait parameters during turning, derived from video-based gait analysis, are promising biomarkers for monitoring postural instability in PD patients.

Supplementary Materials

The online-only Data Supplement is available with this article at https://doi.org/10.14802/jmd.24210.

Conflicts of Interest

The authors have no financial conflicts of interest.

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Author Contributions

Conceptualization: HoYoung Jeon, Jung Hwan Shin, Ri Yu. Data curation: HoYoung Jeon, Min Kyung Kang, Seungmin Lee, Seoyeon Kim, Bora Jin, Kyung Ah Woo. Formal analysis: HoYoung Jeon, Jung Hwan Shin, Ri Yu. Funding acquisition: Jung Hwan Shin, Ri Yu. Investigation: Jung Hwan Shin. Methodology: Jung Hwan Shin, Ri Yu. Software: Ri Yu. Supervision: Han-Joon Kim, Beomseok Jeon. Validation: Ri Yu. Visualization: Jung Hwan Shin. Writing—original draft: HoYoung Jeon, Jung Hwan Shin, Ri Yu. Writing—review & editing: HoYoung Jeon, Min Kyung Kang, Seungmin Lee, Seoyeon Kim, Bora Jin, Kyung Ah Woo, Han-Joon Kim, Beomseok Jeon.

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