



OPEN Sit-to-stand strategies and anticipatory momentum transfer adjustments in individuals with Parkinson's disease using markerless motion capture: a cross-sectional study

Phunsuk Kantha¹, Natcha Charususin², Sunee Bovonsunthonchai³, Jim Richards⁴, Rommanee Rojasavastera¹, Piyaporn Wichaidit⁵, Prayook Jatesiktat⁶, Wei Tech Ang⁷, Prachaya Srivanitchapoom⁸ & Fuengfa Khobkhun²✉

Parkinson's disease (PD) impairs sit-to-stand performance due to bradykinesia and postural instability; however, specific movement strategies and anticipatory momentum transfer adjustments (AMTA) remain unclear. Markerless motion capture offers an accessible alternative to quantify kinematics. This study compared sit-to-stand strategies and AMTA between individuals with PD and healthy controls, and evaluated their correlation with clinical assessments. Fifteen individuals with PD and 15 healthy controls performed a self-selected sit-to-stand (STS) test and the five-times sit-to-stand test (FTSST). Movements of the head, trunk, hip, knee, and ankle were recorded using markerless motion capture across four self-selected STS phases and the FTSST momentum transfer phase. Clinical assessments included the Mini-Balance Evaluation Systems Test (Mini-BESTest), Falls Efficacy Scale-International (FES-I), and the Movement Disorders Society–Unified Parkinson's Disease Rating Scale motor examination (MDS-UPDRS Part III). The PD group required more time to complete both tasks compared to controls (all adjusted $p < 0.050$). During the self-selected STS, individuals with PD exhibited earlier onset of head and trunk movement during Phase I (Flexion Momentum) and lower peak angular extension velocities of the head, hip, and knee during Phase III (Extension) (all adjusted $p < 0.050$). No between-group differences were observed in postural sway during Phase IV (Stabilization) (all adjusted $p > 0.050$). During the FTSST, the PD group demonstrated longer durations for the AMTA1 and AMTA2 sub-phases (adjusted $p = 0.037$). No other kinematic differences remained significant after correction for multiple comparisons (all adjusted $p > 0.050$). Correlation analyses revealed low-to-moderate associations ($|r| = 0.365$ to 0.635 , $p < 0.050$) between clinical outcomes (Mini-BESTest scores and MDS-UPDRS Part III) and kinematic parameters. Individuals with PD exhibit disease-specific sit-to-stand compensation characterized by early head and trunk initiation. During the FTSST, momentum transfer relies primarily on trunk extension rather than lower limb extension. These findings highlight altered segmental coordination strategies and anticipatory duration in PD, which are detectable using markerless motion capture.

Trial registration: The study was registered with the Thai Clinical Trials Registry (TCTR20250112013;

registered on 12/01/2025) prior to data collection. Ethical approval for the study was obtained from the Mahidol University Institutional Review Board, Mahidol University, Thailand (COA No. MU-MOU 2024/330.2612; approved on 26/12/2024) which was carried out fully in accordance with the ethical standard guidelines of the Declaration of Helsinki.

Keywords Parkinson's disease, Sit-to-stand, Anticipatory momentum transfer adjustments, Balance, Markerless motion capture

Abbreviations

AMTA	Anticipatory momentum transfer adjustments
AMTA1	Initial adjustment phase
AMTA2	Late adjustment phase
AP	Anterior-posterior
FES-I	Falls efficacy scale-international
FTSST	Five times sit-to-stand test
H&Y	Hoehn and Yahr
LO	Lift-off
LR	Loading response
MDS-UPDRS	Movement disorders society-unified Parkinson's disease rating scale
Mini-BESTest	Mini-balance evaluation systems test
ML	Medio-lateral
PD	Parkinson's disease
PE	Peak extension
PSIS	Posterior superior Iliac spine
STS	Sit-to-stand
TMSE	Thai mental state examination

¹Research and Innovation Center of Human Movement Sciences, Faculty of Physical Therapy, Mahidol University, Nakhon Pathom, Thailand. ²Parkinson Movement and Research Collaboration Laboratory, Faculty of Physical Therapy, Mahidol University, Nakhon Pathom, Thailand. ³Faculty of Physical Therapy, Mahidol University, Nakhon Pathom, Thailand. ⁴Allied Health Research unit, University of Lancashire, Preston, UK. ⁵Physical Therapy Center, Faculty of Physical Therapy, Mahidol University, Bangkok, Thailand. ⁶Rehabilitation Research Institute of Singapore, Nanyang Technological University, Singapore, Singapore. ⁷School of Mechanical & Aerospace Engineering, Nanyang Technological University, Singapore, Singapore. ⁸Division of Neurology, Department of Medicine, Faculty of Medicine, Siriraj Hospital, Mahidol University, Bangkok, Thailand. ✉email: fuengfa.kho@mahidol.ac.th

Background

Parkinson's disease (PD) is a progressive neurodegenerative disorder characterized clinically by tremor, rigidity, bradykinesia, and postural instability¹. Globally, the prevalence of PD is rising, with the number of people living with the condition estimated to reach approximately 25 million by 2050². In Thailand specifically, the reported prevalence is 706 cases per 100,000 population³. Pathologically, PD is defined by the degeneration of dopaminergic neurons in the substantia nigra pars compacta and the presence of α -synuclein-containing Lewy bodies⁴. This pathology leads to dysfunction of the basal ganglia-cortical circuits, resulting in significant impairments in motor control¹.

Motor symptoms in PD substantially affect daily functioning, particularly in tasks requiring postural control, transitional movements, or coordinated axial rotation^{5–7}. A key contributor to functional decline is postural instability arising from impaired balance control, reduced compensatory adjustments, and axial rigidity^{8,9}. This instability becomes a significant challenge during transitional tasks, where coordinated postural adjustments and sufficient lower limb force generation are essential for safe movement⁹.

The sit-to-stand task is fundamental for walking and maintaining independence^{5,8}. The sit-to-stand movement comprises four distinct phases¹⁰: Phase I (Flexion Momentum), Phase II (Momentum Transfer), Phase III (Extension), and Phase IV (Stabilization). In healthy adults, sit-to-stand is performed smoothly through coordinated ankle movement, trunk flexion, efficient weight transfer, and synchronized extension of the lower limbs¹¹. This efficient movement is supported by intact anticipatory postural adjustments and balance control to achieve equilibrium^{5,12}. Nonetheless, individuals with PD commonly exhibit prolonged movement times, reduced peak joint torques, delayed muscle activation, and impaired joint coordination^{8,13,14}. Consequently, sit-to-stand deficits serve as a sensitive indicator of motor impairment, balance dysfunction, and fall risk in individuals with PD⁵. While the momentum-transfer phase is critical for successful standing, no previous study has specifically examined the anticipatory adjustments during this phase in individuals with PD. Investigating these parameters may elucidate how anticipatory momentum transfer adjustments (AMTA) are modulated to generate and transfer momentum.

To evaluate these movement strategies, studies have traditionally used optical motion capture or inertial sensors^{15,16}. Nevertheless, recent advancements in computer vision and deep learning have enabled the development of markerless motion capture systems^{17,18}. These systems utilize techniques such as pose estimation algorithms to track anatomical keypoint kinematics without physical markers¹⁹. Markerless motion capture offers the distinct advantage of evaluating movement strategies with minimal participant preparation. Furthermore,

it provides new opportunities to investigate biomechanics more comprehensively while improving comfort for participants¹⁶.

Recent validation studies suggest that markerless motion capture systems can estimate spatiotemporal parameters with high accuracy^{20,21}. However, few studies have utilized this technology to isolate the movement strategies of sit-to-stand task in PD. Therefore, the aim of this study was to deploy a markerless motion capture system to identify specific sit-to-stand movement strategies in individuals with PD compared to healthy controls, and to evaluate their association with clinical assessments. We hypothesized that individuals with PD would demonstrate altered movement strategies and impaired anticipatory momentum transfer compared with healthy controls, and that these kinematic deficits would correlate with clinical severity. These findings will provide robust evidence regarding the subtle kinematic compensations distinct to PD motor pathology and support the development of future longitudinal and intervention studies.

Methods

Study design

This cross-sectional study received ethical approval from the Mahidol University Institutional Review Board (COA No. MU-MOU 2024/330.2612; approved on 26/12/2024), and all participants provided written informed consent prior to participation. The study adhered to the Strengthening of the Reporting of Observational Studies in Epidemiology guidelines (Additional File 1). Participants were recruited into two groups: individuals with PD and age- and sex-matched healthy adults. The PD group was recruited from movement disorder clinics in hospitals and physical therapy clinics in Bangkok.

Sample size calculation

Sample size estimation was based on the primary outcome of STS movement time which has been widely used as a clinically meaningful indicator of STS performance in previous studies¹³. Calculations were performed using G*Power (version 3.1.9.4) with an alpha level of 0.05 and a power of 0.80, indicating that 14 participants per group were required. To account for potential attrition, 15 participants were recruited per group.

Participants

The PD group comprised individuals diagnosed with idiopathic PD by a neurologist who met the following inclusion criteria: (1) clinically assessed at stages 2 to 3 on the modified Hoehn and Yahr scale, (2) aged between 45 and 75 years, (3) taking PD medication regularly for at least one month, (4) able to walk independently without any assistive device, and (5) able to follow commands and instructions. The exclusion criteria were: clinically diagnosed dementia or poor cognitive ability, defined as being unable to follow commands or having a Thai Mental State Examination (TMSE) score of < 24/30²²; other disorders such as stroke, severe cardiopulmonary diseases, or musculoskeletal problems that could influence test performance; undergoing hemodialysis; and visual or hearing problems that could not be corrected with the use of aids.

The control group consisted of healthy adults who lived independently, walked without assistive devices, and were capable of following instructions. Control participants were excluded if they had severe systemic illnesses, severe musculoskeletal symptoms, uncorrected sensory impairments, or any verified clinical diagnosis that could affect sit-to-stand performance.

Clinical assessments

Dynamic balance was assessed using the Mini-Balance Evaluation Systems Test (Mini-BESTest), a standardized clinical instrument designed to evaluate balance control across four domains: anticipatory postural adjustments, reactive postural control, sensory orientation, and dynamic gait. The Mini-BESTest consists of 14 items, each scored on a 3-point ordinal scale (0–2). Total scores range from 0 to 28, with higher scores indicating better dynamic balance. This instrument has demonstrated good reliability and validity in individuals with PD and is sensitive to balance impairments²³. A trained assessor administered all evaluations following standardized testing protocols.

Fear of falling was evaluated using the Falls Efficacy Scale-International (FES-I), which quantifies concern about falling during activities of daily living. Participants rated their level of concern on a 4-point Likert scale ranging from 1 (not at all concerned) to 4 (very concerned). Total scores range from 16 to 64, with higher scores indicating a greater fear of falling. The FES-I has shown excellent reliability and validity in both older adults and individuals with PD²⁴.

Finally, disease severity and motor impairment in the PD group were assessed using the motor examination section (Part III) of the Movement Disorders Society–Unified Parkinson's Disease Rating Scale (MDS-UPDRS). This section evaluates motor signs including bradykinesia, rigidity, tremor, postural stability, and gait, with higher scores indicating greater motor severity. The MDS-UPDRS Part III was administered by a neurologist during routine clinical evaluation and was utilized to describe participant's characteristics²⁵.

Markerless motion capture

Kinematic parameters were quantified using a markerless motion capture system that utilizes deep learning-based pose estimation to analyze human movement from synchronized video inputs. This markerless technology has demonstrated high reliability and validity for detecting clinically meaningful kinematic changes during functional movements²⁰. Compared to traditional marker-based systems, this system yielded a mean 3D Euclidean marker position error of 13.23 mm, which is comparable to the precision of manual marker placement between test and retest sessions²⁰. The capture volume was monitored by eight synchronized global-shutter PHX016S cameras (LUCID Vision Labs, Richmond, BC, Canada) (Fig. 1), recording at a resolution of 1440 × 1080 pixels and a frame rate of 60 Hz.

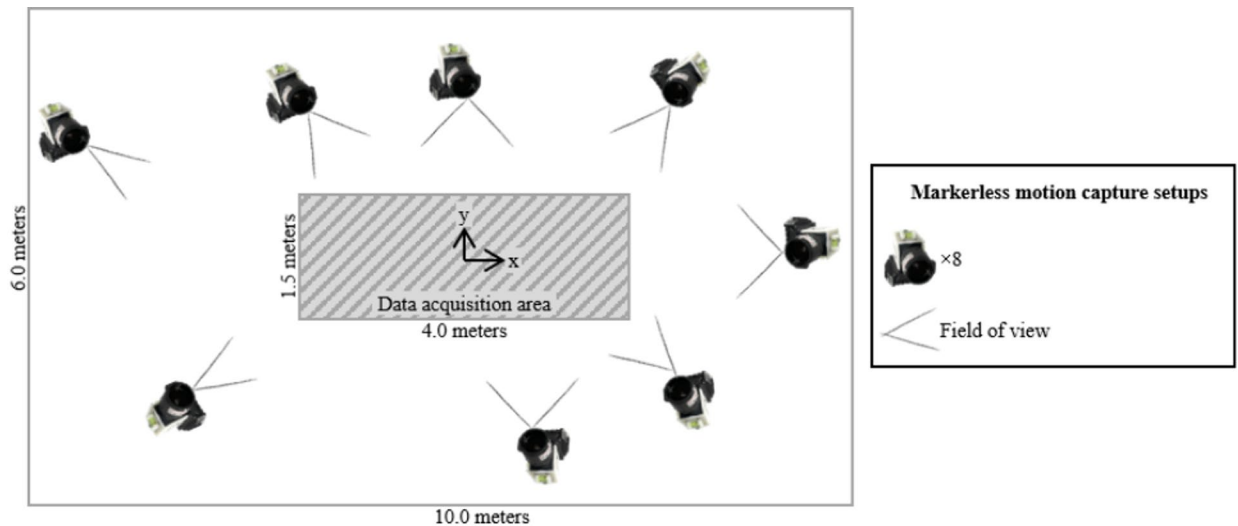


Fig. 1. Experimental setup of the markerless motion capture system.

The system software automatically detected 40 two-dimensional anatomical keypoints from multiple camera viewpoints to reconstruct three-dimensional joint kinematics (Additional File 2), including joint angles and spatiotemporal parameters. Angular displacement and velocity of key segments (head, trunk, hip, knee, and ankle) were analyzed.

Study procedures

Data collection was conducted at the Physical Therapy Center, Faculty of Physical Therapy, Mahidol University. Participants in the PD group were assessed during their medication “ON” state and were instructed to take their prescribed medication 30–45 min prior to data collection. Clinical assessments were administered first, followed by kinematic evaluations. During the kinematic trials, participants performed two trials of a self-selected sit-to-stand test (STS) and the five times sit-to-stand test (FTSST).

Self-selected sit-to-stand test (STS)

Participants began in a seated position on a standard chair (height: 45 cm²⁶ with their knees flexed to approximately 90°. They were instructed to perform a single STS cycle using their natural pattern at a self-selected speed and to remain standing statically for approximately three seconds upon completion²⁶.

Five times sit-to-stand test (FTSST)

Participants sat on the standard chair (height: 45 cm²⁶ and were instructed to perform five consecutive STS cycles as rapidly as possible with their arms crossed over their chest²⁷.

Kinematic data analysis

For each participant, kinematic variables (including segment onset times, peak angular velocities, and sway area) were calculated for each trial and averaged bilaterally (left and right sides). To ensure data reliability, outcomes from the two trials for each task were averaged to provide a single representative value per participant. All outcome measures were extracted from the markerless kinematics dataset using custom MATLAB scripts (R2025a; MathWorks Inc., Natick, MA, USA).

Kinematic data analysis during self-selected sit-to-stand test (STS)

Kinematics of the head, trunk, hip, knee, and ankle segments were analyzed across four distinct phases¹⁰ (Fig. 2).

Phase I (Flexion momentum): This phase initiated when the first moving body segment exceeded three standard deviations (3SD) of its baseline value. The baseline was calculated over a 3-second static sitting period prior to movement initiation. The onset timing of each segment was normalized as a percentage of the total event duration, defined as the interval from the first movement of any segment in *Phase I* to the last movement of any segment in *Phase III*.

Phase II (Momentum transfer): This phase followed *Phase I* and continued until vertical pelvic displacement exceeded 3 cm. The peak angular velocity of each segment was calculated during this phase.

Phase III (Extension): This phase continued from the end of *Phase II* until the last moving segment stabilized within 3SD of the subsequent static standing phase. Similar to *Phase II*, the peak angular velocity of each segment was computed.

Phase IV (Stabilization): This phase was defined as the final 3-second interval following *Phase III*. The height-adjusted sway area²⁸ of the head (midpoint of LHEAD and RHEAD), trunk (T10), and hip (midpoint of LPSIS and RPSIS) segments (Additional File 2) was analyzed during this period.

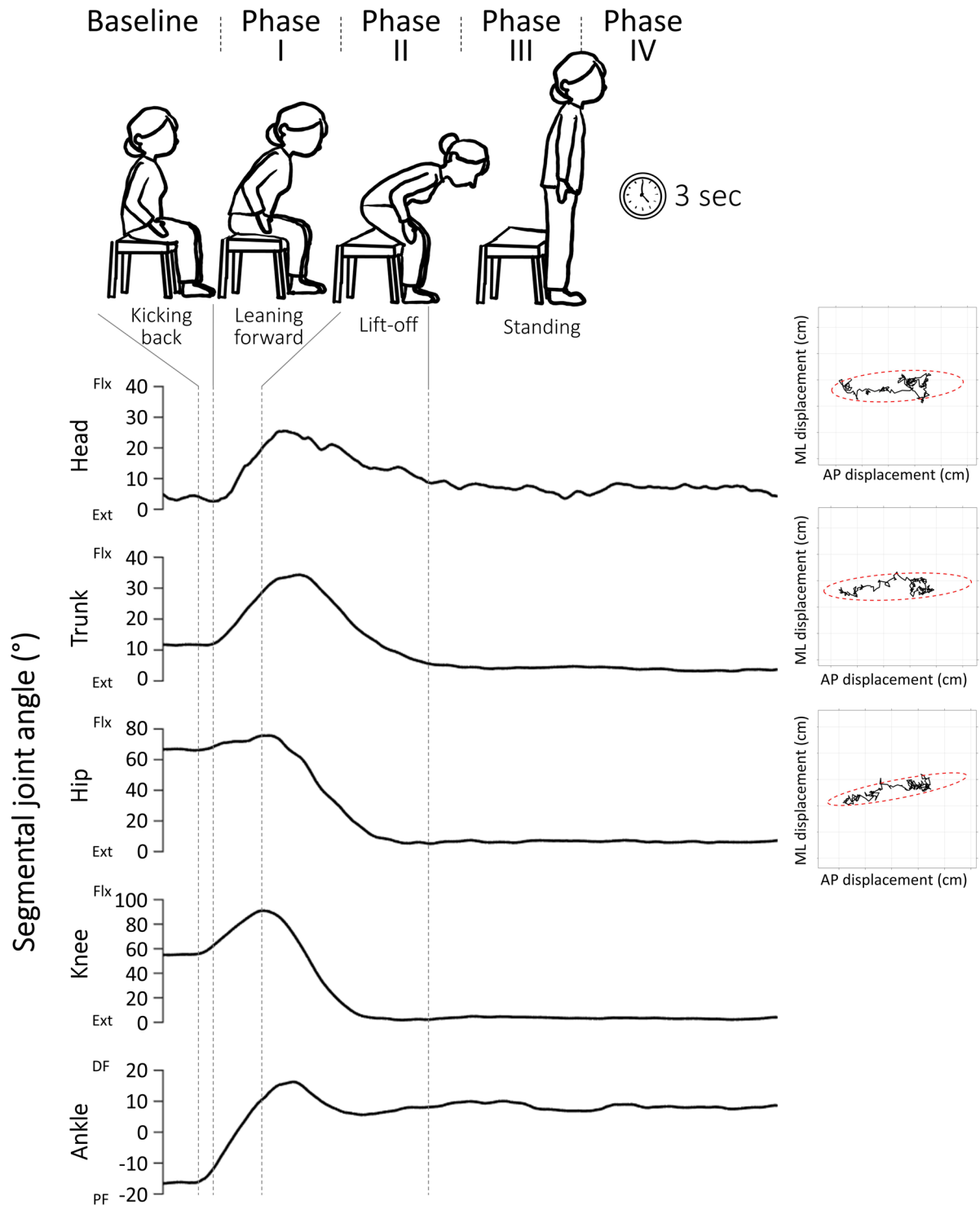


Fig. 2. Segmental joint angles across the four phases of the Self-Selected Sit-to-Stand Test (STS). Abbreviations: AP, Anterior-Posterior; DF, Dorsiflexion; Ext, Extension; Flx, Flexion; ML, Medio-Lateral; PF, Plantarflexion

Kinematic data analysis during five times sit-to-stand test (FTSST)

Kinematic analysis focused on the trunk segment during *Phase II (Momentum Transfer)*. Within this phase, anticipatory momentum transfer adjustments (AMTA) were identified based on three events:

Loading response (LR): The initiation of trunk extension (1st peak flexion).

Peak Extension (PE): The point of maximum trunk extension within this phase.

As illustrated in Fig. 3, the AMTA was subdivided into the initial adjustment phase (AMTA1; from LR to PE) and the late adjustment phase (AMTA2; from PE to LO). The amplitude and time-to-peak of the trunk angle for

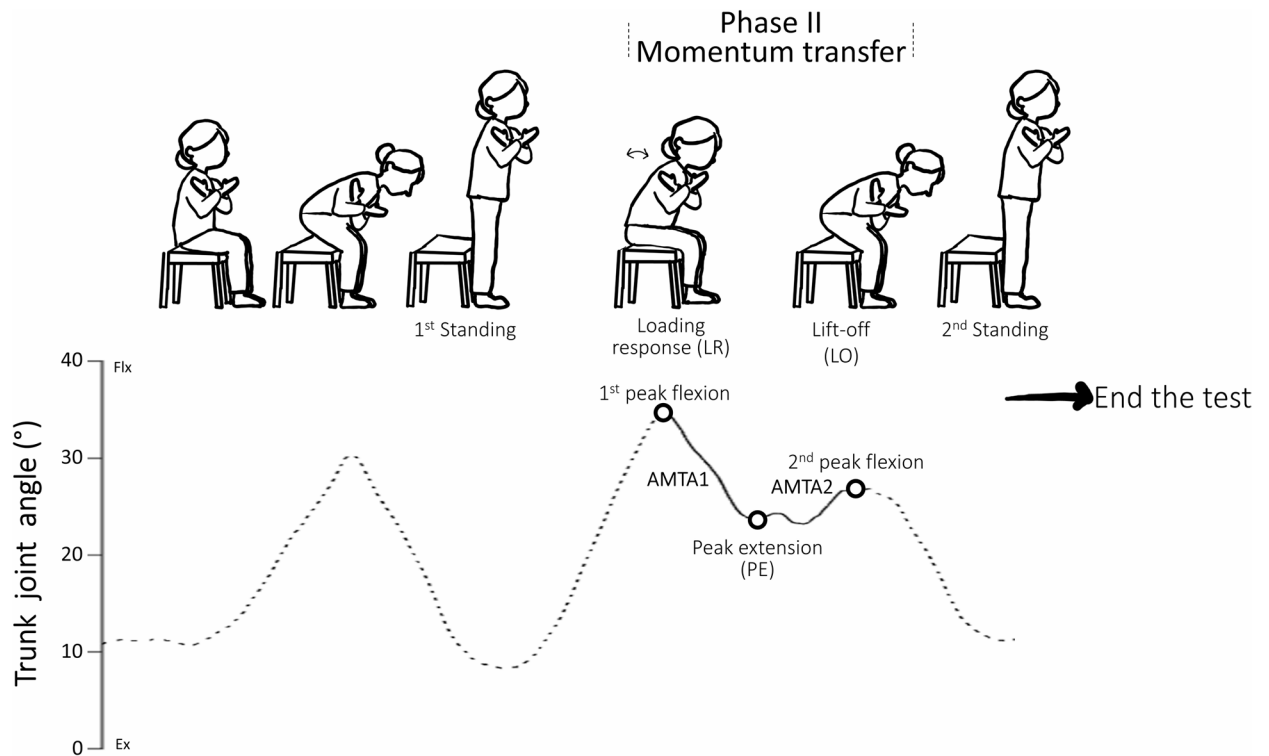


Fig. 3. Anticipatory momentum transfer adjustments (AMTA) of the trunk during *Phase II (Momentum Transfer)* of the Five Times Sit-to-Stand Test (FTSST). Abbreviations: AMTA, Anticipatory Momentum Transfer Adjustments; AMTA1, Initial Adjustment Phase; AMTA2, Late Adjustment Phase; Ext, Extension; Flx, Flexion

both sub-phases were averaged across the middle three cycles. The trunk angle was selected because peripheral joints exhibited a uniform pattern across repetitions and did not actively contribute to primary momentum generation.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows, version 29.0 (IBM Corp., Armonk, NY, USA). The statistical significance threshold was set at $p < 0.05$. Data distribution was assessed using the Shapiro–Wilk test and the majority of variables were found to be normally distributed, supporting the use of parametric analyses. Continuous data are presented as mean $\pm$ standard deviation (SD), whereas categorical data are expressed as frequencies and percentages.

Descriptive statistics were used to summarize participant characteristics and kinematic outcomes. Independent t -tests were used to compare continuous variables between groups, while Chi-square (χ^2) tests were used for categorical variables. To control the Type I error arising from multiple between-group comparisons, the Benjamini–Hochberg False Discovery Rate (FDR) correction was applied. Statistical significance was defined as an FDR-adjusted p -value < 0.05 . In addition, Cohen's d with 95% confidence interval (CI) were calculated and reported. Furthermore, relationships between clinical assessments and kinematic outcomes were assessed using Pearson correlation coefficients. The correlation was interpreted as negligible (0.00 to 0.30), low (0.30 to 0.50), moderate (0.50 to 0.70), high (0.70 to 0.90), or very high (0.90 to 1.00)²⁹.

Results

A total of 32 participants were screened for eligibility; two individuals were excluded due to cognitive impairment. The final study sample consisted of 30 participants: 15 individuals with PD and 15 age- and sex-matched healthy controls (Additional File 1). Detailed demographic and clinical characteristics of all participants are presented in Table 1. The two groups were comparable regarding age, sex, anthropometric characteristics, underlying comorbidities, and cognitive status (all adjusted $p > 0.05$). Individuals with PD exhibited mild-to-moderate disease severity, with a mean modified Hoehn and Yahr stage of 2.30 ± 0.41 and a mean disease duration of 6.53 ± 3.94 years. Additionally, individuals with PD reported a significantly greater fear of falling, as indicated by significantly higher FES-I scores compared to healthy controls ($t = -2.328$, $d = -0.850$ [-1.593, -0.094], adjusted $p = 0.028$).

Regarding clinical outcomes, the PD group exhibited marginally lower Mini-BESTest total scores compared to the control group ($t = 2.772$, $d = 1.012$ [0.241, 1.767], adjusted $p = 0.050$).

Characteristics, unit	Healthy (<i>n</i> = 15)	PD (<i>n</i> = 15)	Adjusted <i>p</i> -value
Age, years	64.73 ± 7.88	66.27 ± 8.52	0.613
Sex, <i>n</i> (%)			
Female	9 (60.0)	9 (60.0)	1.000
Male	6 (40.0)	6 (40.0)	
Weight, kg	57.65 ± 7.29	57.55 ± 12.30	0.979
Height, cm	157.40 ± 5.96	159.46 ± 8.29	0.442
Body mass index, kg/m ²	23.27 ± 2.57	22.50 ± 3.61	0.512
Onset duration of PD, years	–	6.53 ± 3.94	–
Modified H&Y scale, stage 0–5	–	2.30 ± 0.41	–
MDS-UPDRS Part III, score 0–132	–	31.73 ± 15.44	–
Underlying disease, <i>n</i> (%)			
Hypertension	2 (13.3)	4 (26.7)	0.361
Diabetes mellitus	1 (6.7)	0 (0.0)	0.309
Dyslipidemia	3 (20.0)	5 (33.3)	0.409
Others	4 (26.7)	3 (20.0)	0.666
TMSE, score 0–30	28.53 ± 1.41	28.00 ± 2.07	0.417
FES-I, score 16–64	23.67 ± 8.72	32.53 ± 11.90	0.028*
Mini-BESTest			
Anticipatory	5.33 ± 0.82	4.53 ± 1.19	0.068*
Reactive postural control	5.60 ± 1.68	4.53 ± 2.03	0.129
Sensory orientation	5.60 ± 0.74	4.87 ± 1.30	0.089
Dynamic gait	8.73 ± 1.10	7.53 ± 1.55	0.055
Total score, 0–28	25.27 ± 3.47	21.47 ± 4.02	0.050

Table 1. Demographic data and clinical outcome assessments between healthy controls and individuals with Parkinson's disease. Values are presented as mean ± standard deviation or frequency with percentage. Abbreviations: FES-I, Falls Efficacy Scale-International; MDS-UPDRS, Movement Disorder Society–Unified Parkinson's Disease Rating Scale; Mini-BESTest, Mini-Balance Evaluation Systems Test; Modified H&Y, Modified Hoehn and Yahr Scale; PD, Parkinson's Disease; TMSE, Thai Mental State Examination. * indicates a statistically significant difference between groups after the Benjamini–Hochberg False Discovery Rate correction (adjusted $p < 0.05$).

Kinematic results of the self-selected sit-to-stand test (STS)

Table 2 presents the kinematic comparisons between the two groups during the self-selected STS test. Individuals with PD required a significantly longer total duration to complete the STS cycle ($t = -3.728$, adjusted $p = 0.019$). Analysis of temporal sequencing during the flexion momentum phase (Phase I) revealed altered movement initiation strategies in the PD group. Specifically, the onset of head movement ($t = 3.513$, adjusted $p = 0.019$) and trunk movement ($t = 2.807$, adjusted $p = 0.035$) occurred significantly earlier in the movement cycle for participants with PD relative to healthy controls.

During the momentum transfer phase (Phase II), the peak angular velocity of any segment did not change significantly in the PD group (all adjusted $p > 0.050$). During the extension phase (Phase III), peak angular velocities were significantly lower in the PD group for the head ($t = -2.739$, adjusted $p = 0.035$), hip ($t = -2.937$, adjusted $p = 0.033$), and knee ($t = -3.265$, adjusted $p = 0.019$) segments.

During the stabilization phase (Phase IV), segment sway areas for the head, trunk, and hip segments did not differ significantly between groups (all adjusted $p > 0.050$).

Kinematic results of the five times sit-to-stand test (FTSST)

Consistent with the single STS task, the PD group required significantly more time to complete the FTSST ($t = -3.644$, adjusted $p = 0.007$). Trunk kinematics during the momentum transfer phase (Phase II) of the FTSST are presented in Table 3.

During the initial adjustment phase (AMTA1), the PD group exhibited a marginally greater trunk extension amplitude ($t = -2.304$, adjusted $p = 0.052$) and a marginally higher peak angular velocity ($t = -2.213$, adjusted $p = 0.055$) compared to the healthy control group. Furthermore, the durations of the adjustment phases were significantly prolonged in the PD group for both AMTA1 ($t = -2.716$, adjusted $p = 0.037$) and AMTA2 ($t = -2.570$, adjusted $p = 0.037$).

Correlation between clinical assessments and kinematic parameters

The relationships between clinical assessments and kinematic parameters during both sit-to-stand tests are detailed in Fig. 4.

Parameters, unit	Healthy (<i>n</i> = 15)	PD (<i>n</i> = 15)	Cohen's <i>d</i> [95% CI]	Adjusted <i>p</i> -value
Total duration, s	1.74 ± 0.41	2.26 ± 0.34	− 1.361 [− 2.150, − 0.553]	0.019*
Phase I: Flexion momentum				
Head onset, % of cycle	14.85 ± 8.17	6.67 ± 3.83	1.283 [0.483, 2.063]	0.019*
Trunk onset, % of cycle	12.71 ± 8.98	5.34 ± 4.75	1.025 [0.253, 1.781]	0.035*
Hip onset, % of cycle	13.73 ± 8.44	10.46 ± 5.00	0.472 [− 0.258, 1.194]	0.348
Knee onset, % of cycle	6.96 ± 8.80	7.71 ± 7.36	− 0.093 [− 0.808, 0.624]	0.802
Ankle onset, % of cycle	2.20 ± 3.27	5.56 ± 5.51	− 0.743 [− 1.478, 0.005]	0.114
Phase II: Momentum transfer (+)				
Head peak velocity, °/s	110.87 ± 38.98	101.51 ± 29.51	0.271 [− 0.451, 0.988]	0.520
Trunk peak velocity, °/s	65.23 ± 19.85	67.33 ± 22.08	− 0.1 [− 0.815, 0.617]	0.802
Hip peak velocity, °/s	53.69 ± 16.87	59.39 ± 14.89	− 0.359 [− 1.077, 0.366]	0.463
Knee peak velocity, °/s	103.92 ± 46.88	71.85 ± 46.45	0.687 [− 0.056, 1.419]	0.133
Ankle peak velocity, °/s	92.16 ± 26.92	67.59 ± 30.54	0.853 [0.097, 1.596]	0.073
Phase III: Extension (−)				
Head peak velocity, °/s	− 118.64 ± 27.96	− 92.40 ± 24.41	− 1.000 [− 1.754, − 0.230]	0.035*
Trunk peak velocity, °/s	− 70.69 ± 16.02	− 65.79 ± 14.75	− 0.319 [− 1.036, 0.405]	0.463
Hip peak velocity, °/s	− 161.04 ± 24.56	− 134.10 ± 25.67	− 1.072 [− 1.832, − 0.296]	0.033*
Knee peak velocity, °/s	− 170.76 ± 32.25	− 133.42 ± 30.37	− 1.192 [− 1.964, − 0.403]	0.019*
Ankle peak velocity, °/s	− 44.92 ± 11.63	− 35.66 ± 12.12	− 0.779 [− 1.517, − 0.029]	0.100
Phase IV: Stabilization				
Head sway area, cm ²	31.10 ± 14.81	50.98 ± 58.50	− 0.466 [− 1.188, 0.264]	0.348
Trunk sway area, cm ²	42.49 ± 23.51	60.12 ± 65.72	− 0.357 [− 1.076, 0.368]	0.463
Hip sway area, cm ²	54.33 ± 37.23	77.22 ± 92.36	− 0.325 [− 1.043, 0.398]	0.463

Table 2. Kinematic parameters of the self-selected sit-to-stand test between healthy controls and individuals with Parkinson's disease. Values presented as mean ± standard deviation. Abbreviations: CI, Confidence Interval; PD, Parkinson's Disease. * indicates a statistically significant difference between groups after the Benjamini–Hochberg False Discovery Rate correction (adjusted $p < 0.05$).

Parameters, unit	Healthy (<i>n</i> = 15)	PD <i>n</i> = 15	Cohen's <i>d</i> [95% CI]	Adjusted <i>p</i> -value
Total duration, s	8.91 ± 2.05	12.61 ± 3.36	− 1.331 [− 2.116, − 0.526]	0.007*
Phase II: Momentum transfer (+)				
AMTA1 amplitude, °	5.99 ± 6.31	12.47 ± 8.89	− 0.841 [− 1.583, − 0.086]	0.052
AMTA2 amplitude, °	7.75 ± 8.30	11.46 ± 7.91	− 0.459 [− 1.180, 0.271]	0.256
AMTA1 duration, s	0.28 ± 0.20	0.50 ± 0.24	− 0.992 [− 1.745, − 0.223]	0.037*
AMTA2 duration, s	0.26 ± 0.18	0.43 ± 0.17	− 0.938 [− 1.687, − 0.175]	0.037*
AMTA1 velocity, °/s	19.95 ± 11.94	27.36 ± 5.05	− 0.808 [− 1.548, − 0.056]	0.055
AMTA2 velocity, °/s	26.74 ± 23.35	32.44 ± 31.47	− 0.206 [− 0.922, 0.514]	0.578

Table 3. Kinematic parameters of the five-times-sit-to-stand test (FTSST) between groups. Values presented as mean ± standard deviation. Abbreviations: AMTA, Anticipatory Momentum Transfer Adjustments; AMTA1, Initial Adjustment Phase; AMTA2, Late Adjustment Phase; CI, Confidence Interval; PD, Parkinson's Disease. * indicates a statistically significant difference between groups after the Benjamini–Hochberg False Discovery Rate correction (adjusted $p < 0.05$).

Correlation between clinical scores and self-selected sit-to-stand test (STS) kinematics

The total duration of the self-selected STS task demonstrated a moderate correlation with the Modified H&Y scale ($r = 0.562$, $p = 0.029$). Conversely, it showed a low correlation with the Mini-BESTest anticipatory postural adjustments subscale ($r = -0.417$, $p = 0.022$).

During the flexion momentum phase (Phase I), the onset of head movement moderately correlated with MDS-UPDRS Part III scores ($r = 0.635$, $p = 0.011$).

During the momentum transfer phase (Phase II), peak trunk velocity showed low correlations with the Mini-BESTest sensory orientation subscale ($r = -0.365$, $p = 0.047$) and the total score ($r = -0.372$, $p = 0.043$). Additionally, lower extremity (i.e., hip, knee, and ankle) velocities demonstrated low-to-moderate correlations with the Mini-BESTest anticipatory postural adjustments subscale ($r = -0.388$, $p = 0.034$; $r = 0.506$, $p = 0.004$; $r = 0.543$, $p = 0.002$, respectively).

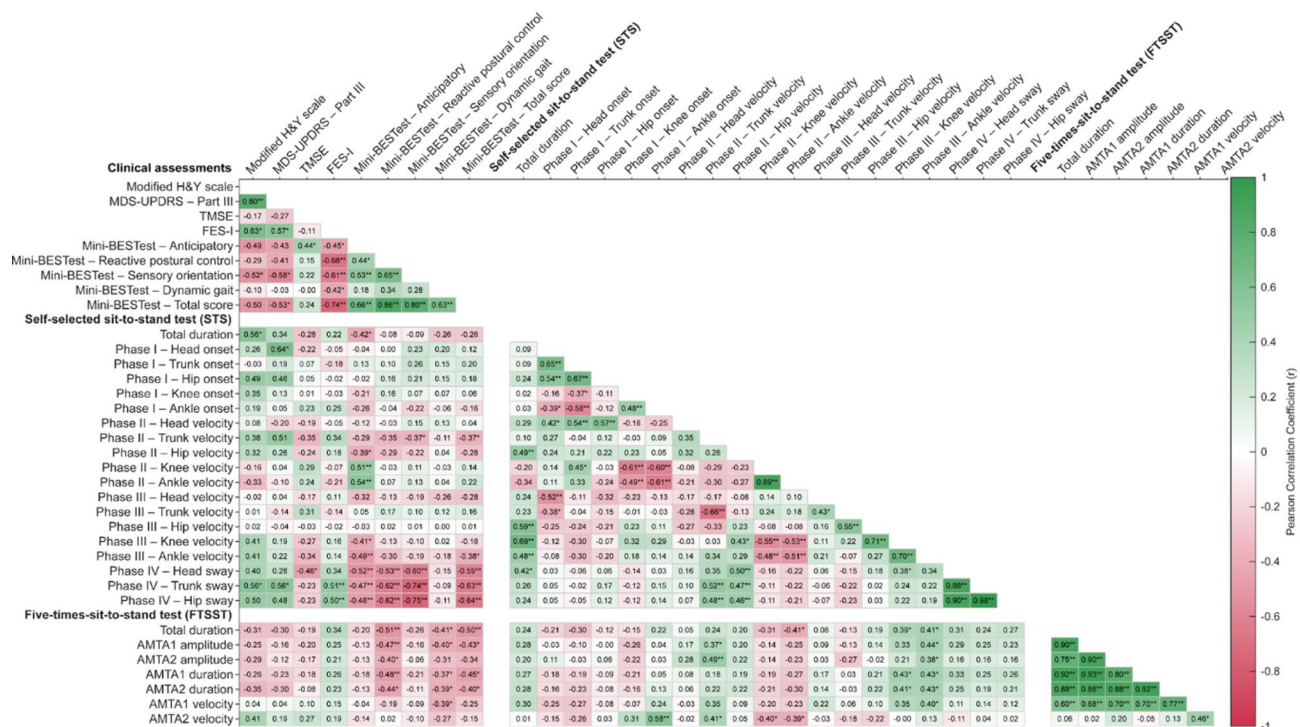


Fig. 4. Correlation matrix between clinical assessments and kinematic parameters during the Self-Selected Sit-to-Stand Test (STS) and the Five Times Sit-to-Stand Test (FTSST). Abbreviations: AMTA, Anticipatory Momentum Transfer Adjustments; AMTA1, Initial Adjustment Phase; AMTA2, Late Adjustment Phase; FES-I, Falls Efficacy Scale-International; MDS-UPDRS, Movement Disorder Society–Unified Parkinson's Disease Rating Scale; Mini-BESTest, Mini-Balance Evaluation Systems Test; Modified H&Y, Modified Hoehn and Yahr Scale; TMSE, Thai Mental State Examination.

During the extension phase (Phase III), peak knee and ankle velocities demonstrated low correlations with the Mini-BESTest anticipatory postural adjustments subscale ($r = -0.409$, $p = 0.025$; $r = -0.488$, $p = 0.006$, respectively). Peak ankle velocity also showed a low correlation with the Mini-BESTest total score ($r = -0.377$, $p = 0.040$).

During the stabilization phase (Phase IV), increased head sway area showed a low correlation with lower TMSE scores ($r = -0.458$, $p = 0.011$). Increased trunk sway area moderately correlated with higher Modified H&Y stage ($r = 0.558$, $p = 0.031$) and MDS-UPDRS Part III scores ($r = 0.562$, $p = 0.029$). Both trunk and hip sway demonstrated low-to-moderate correlations with higher FES-I scores ($r = 0.508$, $p = 0.004$; $r = 0.497$, $p = 0.005$, respectively). Furthermore, increased sway area across all segments (head, trunk, and hip) exhibited low-to-moderate negative correlations with the Mini-BESTest total score and all subscale domains ($p < 0.050$), with the exception of the dynamic gait subscale ($p > 0.050$).

Correlation between clinical scores and five times sit-to-stand test (FTSST) kinematics

Total FTSST duration, AMTA1 amplitude, and AMTA duration demonstrated low-to-moderate negative correlations with the Mini-BESTest reactive postural control subscale, dynamic gait, and total score ($p < 0.050$). The peak AMTA1 velocity demonstrated a low correlation with Mini-BESTest dynamic gait ($r = -0.392$, $p = 0.032$). AMTA2 amplitude showed a low correlation with the Mini-BESTest reactive postural control subscale ($r = -0.402$, $p = 0.028$).

Discussion

This study represents the first application of markerless motion capture to characterize sit-to-stand movement strategies in individuals with PD compared to age- and sex-matched healthy adults. Based on a phase-specific kinematic analysis, individuals with PD exhibited patterns consistent with a compensatory momentum transfer strategy initiated early by head and trunk motion. At the same time, they demonstrated reduced head, hip, and knee extension velocities during the extension phase of the self-selected STS test. Furthermore, during the repetitive and more physically demanding FTSST, this strategy appeared to shift toward a trunk extension-dominant pattern. This shift was characterized by a marginal increase in AMTA amplitude alongside a significantly prolonged AMTA duration. These key kinematic parameters also exhibited low-to-moderate correlations with clinical assessments. Our findings offer preliminary insights into subtle PD-specific kinematic adaptations that clinical assessments may not fully capture.

A key novel finding of this study is the specific momentum adjustment observed during the FTSST. Individuals with PD exhibited marginally greater trunk extension amplitude in the initial adjustment phase

(AMTA1) and significantly longer duration for momentum adjustment. This trend toward increased amplitude and increased duration may reflect a compensatory strategy to generate sufficient forward momentum for rising, potentially offsetting an underlying difficulty in transferring momentum efficiently. This observation is consistent with impaired extensor force generation, as inferred from reduced angular velocities at the hip and knee during the self-selected STS. Consequently, by rapidly extending the trunk, participants may have utilized an inertial strategy to assist in generating the kinetic energy required to propel the body upward. This offers a plausible mechanical explanation for the clinical observation that individuals with PD often experience difficulty generating sufficient forward momentum prior to seat-off³⁰. Furthermore, the negative correlations of these AMTA parameters with reactive postural control and dynamic gait subscales suggest that this trunk-extension strategy is linked to impaired reactive stability and gait control.

Consistent with previous literature³¹, individuals with PD required a significantly longer time to complete both STS tests. However, our segmental sequencing analysis suggests that these temporal delays are accompanied by underlying alterations in coordination strategy. In healthy adults, STS initiation typically begins with ankle movement to facilitate forward center-of-mass displacement¹⁰. In contrast, the PD group exhibited an alteration in this synergistic coordination. Instead, they initiated movement with the head and trunk. This altered sequencing is consistent with impaired movement automaticity and reduced internal cueing associated with basal ganglia dysfunction³² and may be further exacerbated by bradykinesia⁸. It also aligns with the observed clinical deficits, as the early onset of head movement was moderately correlated with higher MDS-UPDRS Part III motor scores. Therefore, the sit-to-stand strategy in individuals with PD appears to shift from a distal, lower-body initiation toward a proximal, trunk-led compensatory mechanism.

Furthermore, the PD group exhibited kinematic features consistent with bradykinesia during the extension phase, evidenced by reduced peak angular velocities across the head, hip, and knee joints during the self-selected STS. This finding aligns with existing research indicating that individuals with PD may experience challenges in generating sufficient joint extensor torque to rise efficiently³³. Interestingly, we found no significant differences in sway area during the stabilization phase (Phase IV) of the self-selected STS. This contrasts with some previous reports of increased post-standing sway in individuals with PD³⁴. The lack of difference may be explained by the mild-to-moderate disease severity of our sample (Modified Hoehn and Yahr stage: 2.30 ± 0.41). It is possible that individuals at this stage retain sufficient static balance control once the dynamic phase of standing is stabilized. Despite the lack of group differences, the sway areas of the head, trunk, and pelvis during Phase IV were still negatively associated with the Mini-BESTest scores. This relationship highlights a state of subclinical post-translational instability that effectively reflects individual balance capacity.

The clinical implications of these kinematic findings suggest a shift in rehabilitation for PD toward targeted neuromechanical re-training, specifically focusing on the timing and coordination of the momentum transfer phase during sit-to-stand tasks. Interventions should prioritize cueing simultaneous ankle movement onset to normalize temporal sequencing, while concurrently implementing power training of the hip and knee extensors to reduce the need for destabilizing momentum generation during the initial adjustment phase.

Study limitations

Several limitations should be considered. First, the cross-sectional design precludes conclusions regarding causality, temporal relationships, or the predictive value of these kinematic markers for PD severity. Second, assessments were conducted only during the “ON” medication state to reflect routine assessment of clinical performance. As motor impairments are typically less pronounced in the “ON” than the “OFF” state³⁵; future studies should examine these outcomes across both medication states. Third, the sample consisted primarily of individuals with mild-to-moderate disease severity and preserved cognitive function, limiting the generalizability of the findings to individuals with advanced PD or cognitive impairment. Fourth, the modest sample size, which was determined based on sit-to-stand movement time, may have limited statistical power for detecting small to moderate effects in some secondary kinematic outcomes and correlation analyses. Fifth, further research is required to establish the test–retest reliability, structural validity, and minimal detectable change of the AMTA1 and AMTA2 variables. Finally, because all sit-to-stand assessments were performed under controlled laboratory conditions using a standardized chair, movement strategies in home or real-world environments may differ.

Conclusions

This study demonstrates that individuals with mild-to-moderate PD adopt distinct compensatory sit-to-stand strategies characterized by altered temporal sequencing and modified momentum regulation. Movement initiation during self-selected STS shifts from a distal, lower-limb-driven pattern to a proximal, trunk-led compensatory mechanism, accompanied by reduced peak joint extension velocities. During the FTSST, this compensation alters into a trunk extension-dominant pattern characterized by prolonged momentum adjustment sub-phase durations and a trend toward increased extension amplitude. These distinct kinematic adaptations exhibit low-to-moderate correlations with clinical scores related to functional mobility in individuals with PD. While these findings highlight the preliminary utility of markerless motion capture for detecting subtle movement compensations, larger longitudinal cohort studies are required. Nonetheless, these insights support the future development of targeted rehabilitation interventions and assessments that consider and prioritize multi-joint coordination sequencing and lower-limb extensor power.

Data availability

The datasets used and analyzed during this study are available from the corresponding author on reasonable request.

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References

- Shin, H. W., Hong, S. W. & Youn, Y. C. Clinical aspects of the differential diagnosis of Parkinson's disease and Parkinsonism. *J. Clin. Neurol.* **18** (3), 259–270 (2022).
- Su, D. et al. Projections for prevalence of Parkinson's disease and its driving factors in 195 countries and territories to 2050: modelling study of Global Burden of Disease Study 2021. *BMJ (Clinical research ed)* **388**:e080952. (2025).
- Muangpaisan, W., Siritipakorn, P. & Assantachai, P. Development of a Thai Parkinson's disease screening tool and the prevalence of Parkinsonism and Parkinson's disease, based on a community survey in Bangkok. *Neuroepidemiology* **49** (1–2), 74–81 (2017).
- Bloem, B. R., Okun, M. S. & Klein, C. Parkinson's disease. *Lancet (London England)*. **397** (10291), 2284–2303 (2021).
- Morris, M. E., Huxham, E., McGinley, J., Dodd, K. & Iansek, R. The biomechanics and motor control of gait in Parkinson disease. *Clin. Biomech. (Bristol Avon)*. **16** (6), 459–470 (2001).
- Nonnekes, J. et al. Neurological disorders of gait, balance and posture: a sign-based approach. *Nat. Rev. Neurol.* **14** (3), 183–189 (2018).
- Khobkhun, F., Santiago, P. R. P., Tahara, A. K., Srivannichapoom, P. & Richards, J. An investigation of the contribution of different turn speeds during standing turns in individuals with and without Parkinson's disease. *Sci. Rep.* **12** (1), 22566 (2022).
- Baizabal-Carvalho, J. F., Alonso-Juarez, M. & Fekete, R. The role of muscle strength in the sit-to-stand task in Parkinson's disease. *Parkinsons Dis* 2023:5016802. (2023).
- Viseux, F. J. F., Delval, A., Defebvre, L. & Simoneau, M. Postural instability in Parkinson's disease: Review and bottom-up rehabilitative approaches. *Neurophysiol. Clin.* **50** (6), 479–487 (2020).
- Schenkman, M., Berger, R. A., Riley, P. O., Mann, R. W. & Hodge, W. A. Whole-body movements during rising to standing from sitting. *Phys. Ther.* **70** (10), 638–648 (1990). discussion 648–651.
- Jeon, W., Jensen, J. L. & Griffin, L. Muscle activity and balance control during sit-to-stand across symmetric and asymmetric initial foot positions in healthy adults. *Gait Posture*. **71**, 138–144 (2019).
- Kotake, T. et al. An analysis of sit-to-stand movements. *Arch. Phys. Med. Rehabil.* **74** (10), 1095–1099 (1993).
- Mak, M. K., Levin, O., Mizrahi, J. & Hui-Chan, C. W. Joint torques during sit-to-stand in healthy subjects and people with Parkinson's disease. *Clin. Biomech. (Bristol Avon)*. **18** (3), 197–206 (2003).
- Mak, M. K. & Hui-Chan, C. W. Audiovisual cues can enhance sit-to-stand in patients with Parkinson's disease. *Mov. Disord.* **19** (9), 1012–1019 (2004).
- Lin, A.-C. et al. Superior gait symmetry and postural stability among yoga instructors—inertial measurement unit-based evaluation. *22*(24), 9683. (2022).
- Das, K., de Paula Oliveira, T. & Newell, J. Comparison of markerless and marker-based motion capture systems using 95% functional limits of agreement in a linear mixed-effects modelling framework. *Sci. Rep.* **13** (1), 22880 (2023).
- Lam, W. W. T., Tang, Y. M. & Fong, K. N. K. A systematic review of the applications of markerless motion capture (MMC) technology for clinical measurement in rehabilitation. *J. Neuroeng. Rehabil.* **20** (1), 57 (2023).
- Faux-Nightingale, A., Philp, F., Leone, E., Helliwell, B. B. & Pandyan, A. Exploring stroke survivors' and physiotherapists' perspectives of the potential for markerless motion capture technology in community rehabilitation. *J. Neuroeng. Rehabil.* **21** (1), 168 (2024).
- Wade, L., Needham, L., McGuigan, P. & Bilzon, J. Applications and limitations of current markerless motion capture methods for clinical gait biomechanics. *PeerJ* **10**, e12995 (2022).
- Jatesiktat, P., Lim, G. M., Lim, W. S. & Ang, W. T. Anatomical-Marker-driven 3D markerless human motion capture. *IEEE J. Biomed. Health Inf.* **29** (9), 6186–6199 (2025).
- Filjtens, B., Ginis, P., Nieuwboer, A., Slaets, P. & Vanrumste, B. Automated freezing of gait assessment with marker-based motion capture and multi-stage spatial-temporal graph convolutional neural networks. *J. Neuroeng. Rehabil.* **19** (1), 48 (2022).
- Muangpaisan, W., Assantachai, P., Sithichai, K., Richardson, K. & Brayne, C. The distribution of Thai Mental State Examination Scores among non-demented elderly in suburban Bangkok metropolitan and associated factors. *J. Med. Assoc. Thai.* **98** (9), 916–924 (2015).
- Löfgren, N., Benka Wallén, M., Sorjonen, K., Conradsson, D. & Franzén, E. Investigating the Mini-BESTest's construct validity in elderly with Parkinson's disease. *Acta Neurol. Scand.* **135** (6), 614–621 (2017).
- Yardley, L. et al. ageing: Development and initial validation of the Falls Efficacy Scale-International (FES-I). *Age Ageing*. **34** 6, 614–619 (2005).
- Keus, S. H. J. M. M. et al. European physiotherapy guideline for Parkinson's disease. 1st ed. *Netherlands* (2014).
- Buatois, S. et al. Five times sit to stand test is a predictor of recurrent falls in healthy community-living subjects aged 65 and older. *J. Am. Geriatr. Soc.* **56** (8), 1575–1577 (2008).
- Albalwi, A. A. & Alharbi, A. A. Optimal procedure and characteristics in using five times sit to stand test among older adults: A systematic review. *Med. (Baltim)*. **102** (26), e34160 (2023).
- Becker, S. et al. Reference values for static posturography of sportive and healthy adults aged 18–30 years. *BMC Sports Sci. Med. Rehabil.* **17** (1), 94 (2025).
- Mukaka, M. M. Statistics corner: A guide to appropriate use of correlation coefficient in medical research. *Malawi Med. J.* **24** (3), 69–71 (2012).
- Inkster, L. M. & Eng, J. J. Postural control during a sit-to-stand task in individuals with mild Parkinson's disease. *Exp. Brain Res.* **154** (1), 33–38 (2004).
- Duncan, R. P., Leddy, A. L. & Earhart, G. M. Five times sit-to-stand test performance in Parkinson's disease. *Arch. Phys. Med. Rehabil.* **92** (9), 1431–1436 (2011).
- Peterson, D. S. & Smulders, K. Cues and attention in Parkinsonian Gait: Potential mechanisms and future directions. *Front. Neurol.* **6**, 255 (2015).
- Inkster, L. M., Eng, J. J., MacIntyre, D. L. & Stoessl, A. J. Leg muscle strength is reduced in Parkinson's disease and relates to the ability to rise from a chair. *Mov. Disord.* **18** (2), 157–162 (2003).
- Mancini, M. et al. Trunk accelerometry reveals postural instability in untreated Parkinson's disease. *Parkinsonism Relat. Disord.* **17** (7), 557–562 (2011).
- Wodarski, P. et al. Trend change analysis of postural balance in Parkinson's disease discriminates between medication state. *J. Neuroeng. Rehabil.* **21** (1), 112 (2024).

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Author contributions

PK, FK, NC, SB and JR conceived and designed the study. FK, PK, WTA, PW, NC, RR, and PS performed the material preparation and data collection. PK, FK, SB and NC analyzed the data. JR, SB, WTA, and PS provided critical interpretation of the results. The first draft of the manuscript was written by PK, FK, and NC, and all authors commented on subsequent versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Ethical approval and consent to participate

This study was approved by the Mahidol University Institutional Review Board (COA No. MU-MOU 2024/330.2612; approved on 26/12/2024). The study was conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent prior to their inclusion in the study.

Consent for publication

Not applicable.

Additional information

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Correspondence and requests for materials should be addressed to F.K.

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