Accepted Article

J Musculoskelet Neuronal Interact 2026

Journal of Musculoskeletal and Neuronal Interactions JMNI

Original Article

Changes in Spatiotemporal Gait Parameter and Functional Mobility Following High Cadence Dynamic Cycling in Parkinson's Disease

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Abstract

Objective: This study examined the changes of 12 sessions of high-cadence dynamic cycling on spatiotemporal gait parameters and functional mobility in older adults with Parkinson's disease (PD). A secondary aim was to investigate the relationships between gait parameters, functional mobility, and PD motor symptoms. **Methods**: Eleven participants with idiopathic PD (74.1±3.9 years; 2 females) completed 12 sessions of high-cadence dynamic cycling. Functional mobility was assessed using the Timed Up and Go (TUG) test. Spatiotemporal gait parameters were measured using inertial measurement unit (IMU) sensors and processed using the GaitPy Python package. PD motor symptoms were assessed using the Movement Disorder Society–Unified Parkinson's Disease Rating Scale Motor III. **Results**: TUG duration changed by 14% (p=0.002). Significant changes were observed in several spatiotemporal gait parameters, including step duration (7.1%), cadence (7.3%), double support time (7.4%), stance (7.1%), and gait speed (9.5%). TUG duration was significantly correlated with stride duration (r=0.756), step duration (r=0.699), cadence (r=-0.656), and gait speed (r=-0.622). MDS-UPDRS Motor III scores were significantly correlated with multiple gait parameters associated with bradykinesia and postural instability including step duration (r=0.673), stride duration (0.655), and stance (0.699). **Conclusions**: High-cadence dynamic cycling was associated with pre-post changes in functional mobility and several spatiotemporal gait parameters in older adults with PD. Detailed gait analysis may help elucidate biomechanical mechanisms underlying mobility improvements following cycling-based rehabilitation.

Keywords: Fall Prevention, Inertial Measurement Unit, Motor Control, Movement Disorder

Introduction

Parkinson's disease (PD) is a progressive neurological disorder that negatively affects functional mobility through its motor symptoms, including tremors, bradykinesia, rigidity, and postural instability[1,2]. Reduced functional mobility significantly impairs essential activities of daily living (ADL), undermining independence and diminishing quality of life (QOL)[3,4]. PD also elevates the risk of falls, which not only increases the risk of injuries and fractures but also fear of falling[5,6]. This fear exacerbates the limitation on mobility and physical activity, forming a cycle of decline[7]. Additionally, there is a significant correlation between functional mobility impairments and cognitive decline, underscoring the multifaceted impact of functional mobility limitations in the PD population[8,9].

Exercise-based interventions have been widely investigated as an adjunct therapy to improve motor function and mobility in individuals with PD[10,11]. Among these interventions, high-cadence dynamic cycling

Angela Ridgel is co-inventor on two patents which are related to the device used in this study: "Bike System for Use in Rehabilitation of a Patient," US 10,058,736. No royalties have been distributed from this patent. The remaining authors have nothing to declare.

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Edited by: G. Lyritis
Accepted 8 June 2026

has emerged as a promising rehabilitation approach. Previous research has shown that high-cadence dynamic cycling, characterized by rapid pedaling rates of 75-85 revolutions per minute (RPM), which is 30% faster than what individuals with PD typically produce on their own can significantly improve functional mobility measured by the timed up and go test (TUG) in individuals with PD[12,13]. The TUG test is a widely used assessment tool to measure functional mobility, balance, and fall risk in clinical populations, including individuals with PD[14,15]. It requires participants to stand up from a seated position, walk three meters, turn around, walk back, and sit down. The test assesses both physical demands and functional performance in PD population[16]. In previous studies, the improvements in functional mobility as measured by the TUG showed reductions of 16.5% and 13% after 3 and 6 sessions of high cadence dynamic cycling, respectively, suggesting a potential therapeutic benefit[12,13].

Despite the reported improvements in functional mobility following high-cadence dynamic cycling, the underlying physiological and biomechanical mechanisms responsible for these changes remain unclear. Previous studies have primarily focused on clinical outcome measures such as TUG performance and motor symptom scores, which provide limited insight into the specific gait adaptations underlying these improvements[12,13,17]. Identifying which spatiotemporal gait parameters contribute to improvements in functional mobility may help clarify the biomechanical mechanisms through which high-cadence dynamic cycling influences motor function in individuals with PD.

Recent advances in wearable sensor technology have enabled more detailed analysis of gait characteristics in clinical populations[18,19]. Inertial measurement unit (IMU) sensors provide objective measurements of body movement and allow the quantification of spatiotemporal gait parameters during walking tasks[20,21]. When combined with computational tools such as the GaitPy Python package, raw IMU sensor data can be processed to extract detailed spatiotemporal gait parameters including step duration, cadence, gait speed, and double support time. These approaches have demonstrated validity and reliability for gait assessment and offer valuable opportunities to better understand mobility changes in individuals with neurological conditions[22,23].

By utilizing IMU-based gait analysis, it is possible to examine how specific spatiotemporal gait parameters change following rehabilitation interventions and how these changes relate to improvements in functional mobility. Therefore, the primary aim of this study was to examine the effects of 12 sessions of high-cadence dynamic cycling on spatiotemporal gait parameters and functional mobility in older adults with PD. A secondary aim was to investigate the relationships between spatiotemporal gait parameters, functional mobility, and PD motor symptoms. Understanding these relationships may help clarify the biomechanical factors contributing to mobility improvements following high-cadence dynamic cycling.

Materials and Methods

Research Design

This study was a secondary data analysis conducted as part of Speed Manipulated Adaptive Rehabilitation Therapy Bike for Parkinson's Disease (SMART) clinical trials (NCT05361200) which was open between April 2022 and July 2023. A companion paper outlining the primary motor symptom outcomes (MDS-UPDRS III) and the TUG results is reported in Kim's paper[24]. Details on the experimental design can be found in Kim[25]. In the parent trial, participants were assigned to two intervention conditions within the high-cadence dynamic cycling protocol. For the purposes of this analysis, these groups were combined into a single cohort because both conditions shared the same primary intervention. Previous findings from the trial demonstrated similar improvements in TUG performance between the two groups (8.7% and 9.0%, respectively)[24], suggesting comparable functional responses. Accordingly, the present study aimed to investigate the mechanisms underlying functional mobility improvements associated with high-cadence dynamic cycling. In this research, we used participants' demographic and PD-related information from the SMART clinical trials. New data collection and analysis were conducted with IMU raw data processing and acquisition of spatiotemporal gait parameters. This approach allowed us to focus on the changes in spatiotemporal gait parameters and examine the association between these parameters and PD motor function in older adults with PD.

Inclusion and Exclusion Criteria

Participants were enrolled if they had a diagnosis of idiopathic PD following the UK Brain Bank Criteria, were between 50 and 79 years of age, stable antiparkinsonian pharmacological treatment for at least six months, and the ability to provide informed consent independently. By establishing these inclusion criteria, we ensured consistency, minimized pharmacological motor fluctuations, and excluded individuals with cognitive decline. Individuals were excluded if they had any uncontrolled cardiovascular, metabolic, or renal health issues that were not cleared by a healthcare professional. To ensure consistency throughout the intervention period, participants were instructed to maintain their usual physical activity levels, physical therapy regimens, and levodopa medication dosages. In addition, participants were asked to maintain consistent medication timing and dosage throughout the 4-week intervention period. This approach was designed to minimize extraneous influences on high-cadence dynamic cycling performance and adaptation, thereby isolating the effects of the intervention itself. The participants' demographic, anthropometric, and PD-related information is presented in Table 1.

Table 1. Participants Demographic, Anthropometric and Parkinson's Disease-Related Information.

Participant	Age	Sex	Height (cm)	Weight (kg)	BMI (kg/m²)	H&Y Stage	LEDD (mg)	Baseline MDS-UPDRS Motor III	HR during Exercise (bpm)
1	73	Female	160	59	23.24	2	300	69	77.81
2	75	Male	182	118	35.33	2	800	37	84.3
3	78	Male	185	84	24.45	2	800	39	76.1
4	72	Female	165	56	20.83	1	300	17	89.0
5	69	Male	182	90	27.17	2	100	25	75.3
6	78	Male	180	87	26.83	1	1405	27	87.0
7	79	Male	185	109	31.96	3	600	31	73.2
8	75	Male	195	88	23.17	3	200	60	87.7
9	69	Male	175	100	32.55	1	900	17	87.1
10	69	Male	174	77	25.43	2	300	16	100.3
11	78	Male	172	71	23.83	2	300	29	80.7

Note. Abbreviations: H&Y, Hoehn and Yahr; BMI, Body Mass Index; LEDD, Levodopa equivalent daily dose; MDS-UPDRS Motor III, Movement Disorder Society–Unified Parkinson's Disease Rating Scale Motor II; HR, Heart Rate.

High-Cadence Dynamic Cycling

High-cadence dynamic cycling is a therapeutic exercise intervention performed using stationary motorized bicycle that enables individuals with PD to pedal at a 30% faster cadence (75-85rpm) than they typically produce on their own[12]. The high-cadence dynamic cycling motor is driven by a programmable logic controller written to simulate forced tandem cycling by adjusting the pedaling speed based on the rider's performance. The motor speed is set between 75-85 revolutions per minute (rpm), and the motor torque adjusts to changes in pedal force. The motor performs most of the work, but the participant must still actively pedal, which is encouraged by a gamified on-screen animation. In this study, each participant completed 12 sessions of high-cadence dynamic cycling, three days per week for four weeks. Each high-cadence dynamic cycling session consisted of 5 minutes of warm-up at 60 revolutions per minute (RPM), 30 minutes of the main dynamic cycling session at 80 RPM, and 5 minutes of cool-down at 60 RPM. The 30-minute duration for high-cadence dynamic cycling sessions was based on previous research[12,13] showing that the exercise intensity, measured by heart rate, corresponds to moderate-intensity exercise. This duration was selected to provide sufficient physiological benefits while minimizing the risk of adverse events in older adults with PD. There was a 48-hour resting interval between each exercise session to prevent excessive muscle fatigue and allow participants to fully recover. This rest period was designed to optimize participant health and ensure they could perform subsequent high-cadence dynamic cycling sessions with optimal effort and safety. To avoid the group training effect, high-cadence dynamic cycling was conducted in an individual setting. Certified exercise physiologists and research assistants were present with each participant to monitor and ensure the quality of the high-cadence dynamic cycling training sessions. No adverse events, near-falls, intolerance, or withdrawals due to safety concerns were reported during the intervention period. A total of 13 participants were recruited at the beginning of the study. Of these, one participant withdrew before completing the intervention, and 12 participants completed all 12 sessions of high-cadence dynamic cycling without any absences. For the secondary analysis, one participant was excluded from the analysis due to insufficient IMU data, as only two gait cycles were detected, which did not meet the minimum requirement for reliable spatiotemporal gait parameter estimation.

Functional Mobility

Functional mobility was measured during the timed up and go (TUG) test. The TUG highly correlates to functional mobility in individuals with PD and has demonstrated reliability and validity[26,27]. The TUG test was conducted in a university laboratory on a hard floor surface. The chair used for the test had a height of 50 cm and was equipped with two arms to ensure participant safety during the standing and sitting phases. Participants were instructed to avoid using the chair arms during the test unless necessary for safety. To ensure consistency, the same chair and testing environment were used for both the baseline and follow-up assessments. Participants

wore Ambulatory Parkinson's Disease Monitoring (APDM) OPAL IMU sensors during the TUG test. It features 3-axis accelerometers, gyroscopes, and magnetometers that enable precise motion detection in all three dimensions (X, Y, and Z axes). The sensors operate at a sampling rate of 128 Hz, providing high-resolution data for accurate monitoring of mobility and gait dynamics, including posture changes and turning dynamics[28]. A total of five sensors were utilized in this protocol. Two sensors were attached to their feet, two to the both wrists, and one to the lumbar region. Although multiple IMUs were used during data collection as part of the APDM system, only the lumbar-mounted sensor data were utilized for GaitPy processing to derive spatiotemporal gait parameters. The additional sensors were used exclusively within the APDM Mobility Lab software to quantify overall TUG performance metrics, including total duration and transitional movements such as turn duration and sit-to stand time. Individuals were instructed to stand up from the chair when they heard the start cue from the APDM Mobility lab software, walk forward to a cone 3 meters away, turn around, walk back to the chair, and sit down. The TUG test was performed at the baseline visit and after 12 sessions of high-cadence cycling. To avoid the learning effect on the TUG test, we ensured a four-week interval between the baseline TUG assessment and the follow-up TUG test.

Spatiotemporal Gait Parameters

Raw acceleration data along with millisecond time stamps were extracted directly from the IMU sensors. Participant height was obtained at the baseline visit. Raw accelerometer, timestamps and height data were then processed using the GaitPy Python package (version 1.6.0), an open-source algorithm tailored for gait analysis. Raw IMU data were processed without explicit segmentation of walking, turning, or transitional phases. Gait cycles were identified automatically by the GaitPy algorithm. The main functionalities of the GaitPy package include the classification of gait bouts, the extraction of spatiotemporal gait parameters from each gait cycle, and the visualization of the detected gait bout. This program provides detailed analysis within a single gait cycle by extracting 20 specific gait parameters, providing an in-depth look at an individual's gait dynamics[22]. By implementing the GaitPy Python package in Python 3.6.8 version (Python Software Foundation, Wilmington, DE), spatiotemporal gait parameters were captured including step duration (seconds), stride duration (seconds), cadence (steps per minute), initial and terminal double support time (seconds), single limb support (seconds), stance (distance covered while one foot is in contact with the ground; meters), swing (distance covered while the foot is in the air; meters), step length (distance between the heel strike of one foot and the subsequent heel strike of the opposite foot; meters), stride length (distance between the heel strike of the same foot in two consecutive steps; meters), and gait speed (meters per second). For data filtering, GaitPy's built-in post-processing filters were applied to exclude physiologically implausible stride detections, including strides longer than 2.25 seconds or shorter than 0.25 seconds, strides with stance times exceeding 70% of the maximal stride time, and strides with initial double support exceeding 20% of the maximal stride time[29,30]. In addition, outlier values were excluded using a ±2 standard deviation criterion for each parameter. Due to the variability in the number of gait cycles detected during the TUG test between participants, we calculated the average value of each spatiotemporal gait parameter from these detected cycles for our data analysis.

PD Motor Symptoms

Participants' PD motor symptoms were measured using the Movement Disorder Society-Sponsored Revision of the Unified Parkinson's Disease Rating Scale Motor III (MDS-UPDRS Motor III) which is the most widely used clinical rating scale for PD[31]. It consists of 33 items, each scored on a scale from 0 to 4, where 0 indicates normal function and 4 indicates extreme impairment or inability. The total MDS-UPDRS Motor III score ranges from 0 to 132, with higher scores reflecting greater severity of PD-related motor symptom impairment[32]. To ensure unbiased assessment, ratings were videotaped and subsequently scored by a blinded reviewer trained in the MDS-UPDRS Motor III assessment[33]. The assessment of rigidity was conducted in person by an experienced assessor for all participants.

Statistical Analysis

First of all, we performed the Shapiro-Wilk test to assess the normality of all variables. The results indicated that all variables were normally distributed ($p > 0.05$). Based on this, we proceeded with parametric statistical analyses for this study. Descriptive statistical analysis was used to calculate the mean and standard deviation for demographic variables. A paired sample t-test was conducted to determine the difference between two time points, pre-and post-intervention, on TUG-related variables and spatiotemporal gait parameters. For this secondary analysis, TUG time and gait speed (m/s) were defined as the primary outcomes, as they represent functional mobility and overall gait performance, respectively. All other variables were considered exploratory. Given the number of comparisons and the small sample size, all p-values are reported as unadjusted. Pearson's correlation coefficient (two-tailed) was used to identify correlations between MDS-UPDRS Motor III score, functional mobility, and spatiotemporal gait parameters. The baseline spatiotemporal gait parameters, TUG time, and baseline MDS-UPDRS Motor III scores were utilized for Pearson's correlation coefficient. For all statistical analysis, IBM SPSS version 28 (Armonk, NY: IBM Corp)

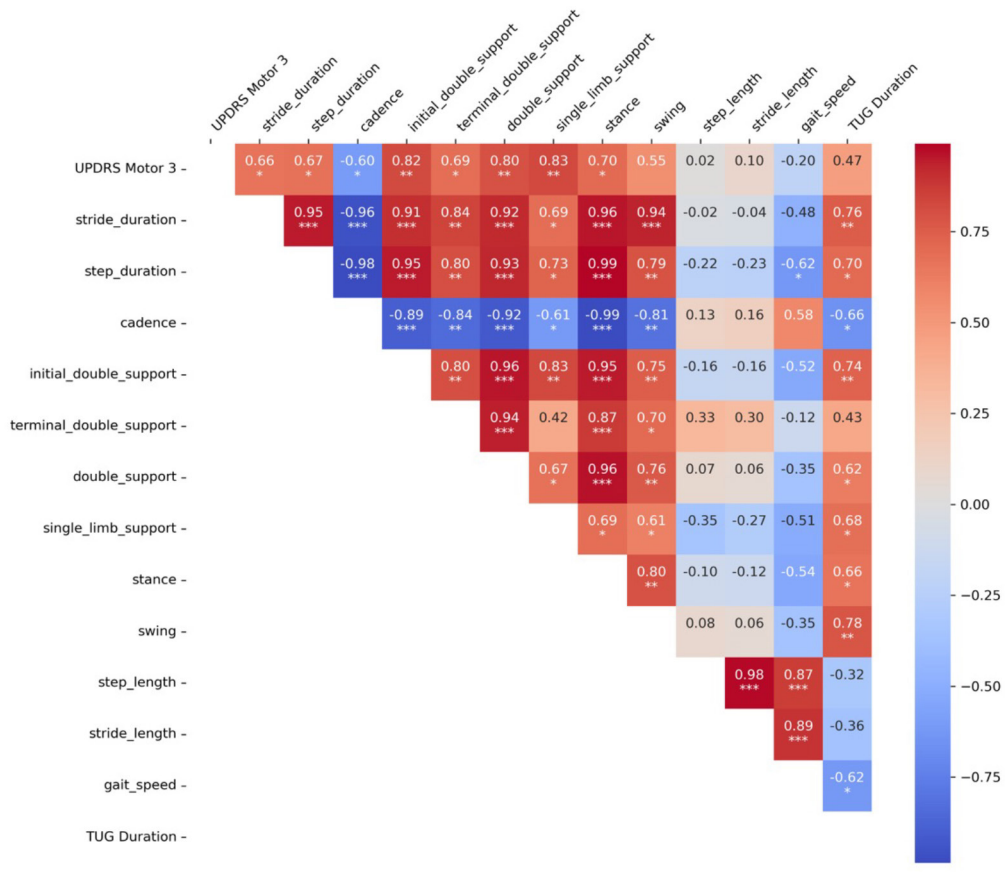

Figure 1. Correlation Matrix with Significance Levels for Spatiotemporal Gait Parameters, TUG and UPDRS Motor III Scores. This heatmap illustrates the Pearson correlation coefficients between various spatiotemporal gait parameters, Timed Up and Go (TUG), and the Unified Parkinson's Disease Rating Scale (UPDRS) Motor III scores. The values range from -1 to 1 and are represented by a color gradient from blue (negative correlation) to red (positive correlation). Significant correlations are indicated by asterisks, with * representing p < 0.05, ** representing p < 0.01, and *** representing p < 0.001. The study analyzed various spatiotemporal gait parameters, such as stride duration, step duration, cadence, initial double support, terminal double support, double support, single limb support, stance, swing, step length, stride length, gait speed, and TUG duration. The results showed significant correlations among most of these parameters.

and Python version 3.12 (Python Software Foundation, Wilmington, DE) were used. Statistical significance was set at 0.05.

Results

Correlations Between Spatiotemporal Gait Parameter, Functional Mobility, and PD-Motor Symptoms

Results of the correlation analysis are shown in Figure 1. We found significant correlations between the spatiotemporal gait parameters, the functional mobility, and the PD motor function, respectively. There were significant correlations between the baseline MDS-UPDRS Motor III score and stride duration (r=0.655, p=0.026), step duration (r=0.673, p=0.023), cadence (r=-0.603, p=0.05), initial double support time (r=0. 816, p=0.002), terminal double support time (r=0.688, p=0.019), total double support time (r=0.796, p=0.003), single limb support time (r=0.827, p=0.002), and stance (r=0.699, p=0.017). There were also significant correlations between TUG duration and stride duration (r=0.756, p=0.007), step duration (r=0.699, p=0.017), cadence (r=-0.656, p=0.029), initial double support time (r=0.737, p=0.010), total double support time (r=0.623, p=0.040), single limb support time (r=0.680, p=0.021), stance (r=0.664, p=0.026), swing (r=0.781, p=0.005), and gait speed (r=-0.622, p=0.041). Within the spatiotemporal gait parameters, walking cadence was negatively correlated with stride duration (r=-0.956, p<0.001), step duration (r=-0.982, p<0.001), initial double support time (r=-

Table 2. Changes of TUG and Spatiotemporal Gait Parameters.

	Variables	Pre	Post	*t*	Cohen's *d*	Δ Mean (95% CI)	*p*
TUG Related Variables	TUG Duration (s)	11.93±2.73	10.25±2.52	4.205	1.270	1.68 (0.78, 2.57)	**0.002**
	Turn Angle (°)	177.64±9.54	177.45±21.34	0.033	0.010	0.18 (-12.05, 12.42)	0.974
	Turn Duration (s)	2.93±0.32	2.78±0.49	0.881	0.270	0.15 (-0.22, 0.52)	0.399
	Turn Velocity (°/s)	145.18±32.02	149.27±28.52	-0.856	0.258	-4.09 (-14.74, 6.55)	0.412
	Sit to Stand (s)	1.36±0.58	1.01±0.25	1.536	0.466	0.35 (-0.15, 0.86)	0.155
	Stand to Sit (s)	1.02±0.24	1.13±0.25	-1.081	0.352	-0.10 (-0.33, 0.11)	0.308
Spatiotemporal Gait Parameters	Stride Duration (s)	1.14±0.08	1.09±0.10	1.551	0.558	0.04 (-0.01, 0.11)	0.152
	Step Duration (s)	0.56±0.04	0.52±0.04	3.840	1.291	0.03 (0.016, 0.06)	**0.003**
	Cadence (Steps/minute)	107.47±7.98	115.38±10.06	-3.556	1.072	-7.90 (-12.86, -2.95)	**0.005**
	Initial Double Support (s)	0.13±0.012	0.12±0.013	3.038	0.959	0.01 (0.003, 0.02)	**0.012**
	Terminal Double Support (s)	0.14±0.011	0.13±0.013	2.540	0.788	0.01 (0.001, 0.02)	**0.029**
	Total Double Support (s)	0.27±0.02	0.25±0.025	3.019	0.827	0.02 (0.006, 0.04)	**0.013**
	Single Limb Support (s)	0.47±0.12	0.42±0.05	1.498	0.464	0.05 (-0.02, 0.12)	0.165
	Stance (m)	0.70±0.05	0.65±0.05	3.611	1.167	0.04 (0.019, 0.08)	**0.005**
	Swing (m)	0.43±0.04	0.44±0.07	-0.198	0.131	-0.004 (-0.05, 0.04)	0.847
	Step Length (m)	0.47±0.07	0.49±0.09	-1.515	0.397	-0.02 (-0.05, 0.01)	0.161
	Stride Length (m)	0.95±0.14	0.99±0.17	-1.454	0.438	-0.04 (-0.10, 0.02)	0.177
	Gait Speed (m/s)	0.84±0.14	0.92±0.21	-2.957	0.837	-0.08 (-0.14, -0.02)	**0.014**

Note. Values are reported as mean ± standard deviation. Abbreviations: s, Seconds; °, Degree; °/s, Degree per second; m, Meters; m/s, Meters per second. TUG, Timed Up and Go; CI, Confidence Interval; All p-values are unadjusted and interpreted as exploratory.

0.894, $p<0.001$), terminal double support time ($r=-0.845$, $p=0.001$), total double support time ($r=-0.917$, $p<0.001$), single limb support time ($r=-0.614$, $p=0.045$), stance ($r=-0.986$, $p<0.001$), and swing ($r=-0.811$, $p=0.002$). Gait speed was negatively correlated with stride duration ($r=-0.623$, $p=0.04$), but positively correlated with stride length ($r=0.867$, $p=0.001$) and step length ($r=0.893$, $p<0.001$). Based on the results of the correlation analysis, we confirmed that higher MDS-UPDRS Motor III scores and longer TUG durations were significantly associated with longer stride and step durations, increased double support times, and decreased cadence and gait speed. These findings suggest that individuals with more severe motor impairment (as indicated by higher MDS-UPDRS Motor III scores) and poorer functional mobility (as indicated by longer TUG durations) tend to have slower, less efficient gait patterns. This relationship highlights how motor symptom severity and reduced functional mobility affect gait performance in older adults with PD.

Functional Mobility Changes

A paired samples t-test revealed a significant improvement in TUG duration (14%; $t=4.205$, $p=0.002$) after 12 sessions of high-cadence cycling. Although there were improvements in mean turn duration (5.1%; $t=0.881$, $p=0.399$), and sit-to-stand duration (25.7%; $t=1.536$, $p=0.155$), these improvements were not statistically significant (Table 2).

Spatiotemporal Gait Parameter Changes

In terms of spatiotemporal gait parameter changes (Table 2, Figure 2), a paired samples t-test showed significant changes in step duration (7.1%; $t=3.840$, $p=0.003$), cadence (7.3%; $t=-3.556$, $p=0.005$), initial double support time (7.6%; $t=3.038$, $p=0.012$), terminal double support time (7.1%; $t=2.540$, $p=0.029$), total double support time (7.4%; $t=3.019$, $p=0.013$), stance (7.1%; $t=3.611$, $p=0.005$), and gait speed (9.5%; $t=-2.957$, $p=0.014$) after 12 sessions of high-cadence dynamic

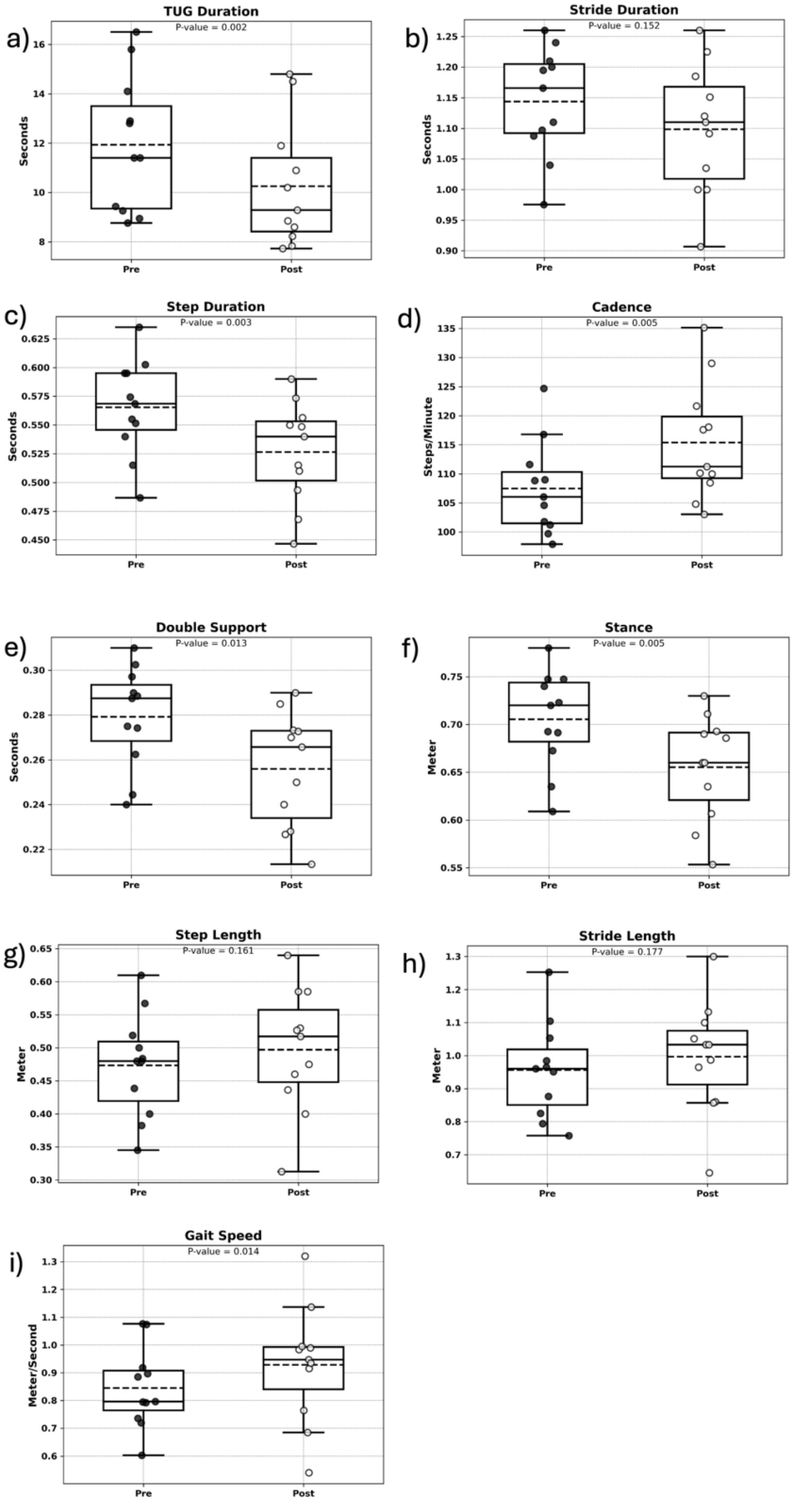

Figure 2. Comparison of Pre and Post Intervention TUG and Spatiotemporal Gait Parameters Derived from the IMU Sensors. Box-and-whisker plots for a) TUG duration, b) stride duration c) step duration, d) cadence, e) total double support, f) stance, g) step length, h) stride length, i) gait speed. Black dots represent each participant's pre-intervention data points, while white dots represent the post-intervention data points. The dashed horizontal line within each box represents the mean, and the solid horizontal line represents the median. The boxes themselves represent the interquartile range, which encompasses the middle 50% of the scores. The whiskers extending from the boxes represent the range of scores outside the middle 50%, except for outliers, which are shown as single points beyond the whiskers.

cycling. Non-significant improvements were found in stride duration (4.4%; t=1.551, p=0.152), single limb support time (10.6%; t=1.498, p=0.165), swing (2.3%; t=-0.198, p=0.847), step length (4.2%; t=-1.515, p=0.161), and stride length (4.2%; t=-1.454, p=0.177).

Discussion

This study aimed to evaluate the impact of 12 sessions of high-cadence dynamic cycling on spatiotemporal gait parameters and functional mobility in older adults with PD. Additionally, it aimed to explore the correlations between these gait parameters, functional mobility, and PD motor symptoms. We found significant correlations between MDS-UPDRS Motor III scores and step duration and stride duration. In addition, functional mobility was significantly correlated with several spatiotemporal gait parameters, including cadence and gait speed. Following the 12 sessions of high-cadence cycling, significant enhancements in functional mobility were observed. After 12 sessions of intervention, the TUG time changed from 11.93 ± 2.73 seconds before the intervention to 10.25 ± 2.52 seconds afterwards, which was consistent with previous studies[12,13]. Although these improvements did not reach the minimal detectable change (MDC) of 3.5 seconds for the PD population[34], the shift towards a TUG time of 10 seconds is potentially meaningful. Although the observed change did not exceed the MDC threshold, shifts toward clinically meaningful TUG categories may still reflect functional benefits and a potential reduction in fall risk in individuals with PD. Specifically, a TUG time exceeding 12 seconds suggests a higher risk of falls and balance impairments[35], while a TUG time of 10 seconds is considered good functional mobility and may have a lower risk of falls in the individuals with PD population[36]. These findings underscore the practical relevance of high-cadence dynamic cycling on functional mobility in individuals with PD. In addition, we have also observed non-significant improvements in turn angle, turn duration, turn velocity, and sit-to-stand time in TUG-related variables. The improvements in spatiotemporal gait parameters after high-cadence cycling are comparable to previous research showing that 11 weeks of resistance training led to improvement in TUG performance[37]. High-cadence dynamic cycling offers unique benefits, particularly for older adults with PD who may not be able to safely perform high-intensity resistance exercise, and it may serve as a more accessible option for this population. In addition, high-cadence dynamic cycling incorporates components of velocity motor training with faster cadence (75-85 rpm). It has been hypothesized that these components may promote sensory feedback from the periphery, and stimulates activation of the basal ganglia circuits[38]. These proposed mechanisms may contribute to the observed improvements and could be highly beneficial to clinical populations, particularly those with neurological conditions.

Additionally, by employing IMU sensors and implementing the GaitPy Python package, we overcame limitations from previous studies in our lab[12,13], which had not explored the influence of high-cadence cycling on these spatiotemporal gait parameters and their relationship to functional mobility. Our refined methodology revealed significant improvements in various spatiotemporal gait metrics such as step duration, cadence, initial, terminal, and total double support times, stance length, and gait speed. These findings are supported by the work of Linder et al[39], who found that an 8-week aerobic cycling program significantly changed gait speed by 0.04m/s, cadence by 4 steps/min, and stance by 1.5% in the PD population. The improvement in gait speed of 0.08 m/s is particularly noteworthy. This increase falls within the minimal clinically important difference (MCID) range of 0.05-0.22 m/s, and also meets the small important difference (SID) of 0.06 m/s for individuals with PD[40]. While the exact physiological and biomechanical mechanisms underlying improvements in gait speed are still unknown, there are plausible hypotheses. It is hypothesized that high-cadence cycling, particularly pedaling at 80 rpm, directly contributes to a faster step cadence. This increase in pedaling cadence naturally leads to faster leg movements and a faster gait cycle, thereby increasing both step cadence and overall gait speed. In addition, our analysis revealed a significant correlation between gait speed and key spatiotemporal gait parameters, such as step and stride length and step duration. Furthermore, the observed improvements in step duration suggest that the increase in gait speed may be related to changes in these spatiotemporal gait parameters induced by the high-cadence dynamic cycling intervention. These findings highlight the effectiveness of high-cadence cycling in modifying spatiotemporal gait parameters to improve gait speed. Furthermore, previous research[41] has reported that speed-based exercise facilitates locomotor central pattern generators and increases stride frequency. Based on these findings, we hypothesize that high-cadence dynamic cycling similarly facilitates locomotor adaptations during walking by improving neuromotor coordination and enhancing rhythmic movement patterns. In addition, high-cadence dynamic cycling has been shown to improve bradykinesia symptoms[24], which subsequently leads to positive changes in gait parameters, including increased gait speed, cadence, and reduced stride duration.

We observed significant improvements in initial, terminal, and total double support times as well as stance variables after twelve sessions of high-cadence dynamic cycling. These improvements are critical for older adults with PD because they are closely related to gait stability, dynamic balance, and postural stability which are key determinants of fall risk[42]. Reductions in double support time may be associated with improvements in gait stability and dynamic balance, factors that have been linked to fall risk in neurological populations[43]. We hypothesize that the specific characteristics of high-cadence dynamic cycling, continuous and repetitive motion of pedaling at

a high-cadence, may lead to improved neuromuscular coordination and adaptations, as well as improved proprioception. These improvements, in turn, contribute to the observed improvements in double support time and stance variables. This hypothesis is supported by previous research conducted in our lab, which indicated that high-cadence dynamic cycling improves lower-body proprioceptive sensitivity. Specifically, participants who engaged in high-cadence dynamic cycling demonstrated significantly improved tibiofemoral joint repositioning accuracy at 70 degrees compared to those in a static cycling group[44].

Our study found significant correlations between functional mobility, as measured by TUG time, and various spatiotemporal gait parameters, including stride duration, step duration, double support time, stance, swing, and gait speed. Following twelve sessions of high-cadence dynamic cycling, we observed significant improvements in TUG time, step duration, cadence, double support time, stance, and gait speed. From these correlations and observed improvements, it is reasonable to assume that the enhancements in functional mobility post-intervention may be related to increases in movement speed (step duration, cadence, gait speed) and postural stability (double support). These elements are crucial for the functional mobility of older adults with PD and are in line with prior studies indicating that improvements in spatiotemporal gait parameters lead to better TUG times[45,46]. We also found significant correlations between stride duration, step duration, cadence, and both double and single limb support times, as well as stance and MDS-UPDRS Motor III scores, encompassing. We also found strong inverse correlations between cadence and stride/step duration; however, these relationships represent mathematically interdependent components of spatiotemporal gait analysis rather than independent physiological discoveries. Such correlations underscore the profound influence of PD motor function impairments on spatiotemporal gait parameters and reinforce the value of measuring spatiotemporal gait parameters as comprehensive and objective tools in monitoring the progression of PD.

This study has several limitations. First, the small sample size may limit the statistical power of our analysis. We did not find significant correlations between functional mobility and PD-related motor symptoms, a finding that differs from the conclusions of many previous studies[47]. In addition, given the small sample size and the absence of correction for multiple comparisons, all reported p-values should be interpreted as exploratory and unadjusted. The second limitation of our study is the absence of a control group. Without a control group, it is difficult to compare the effects of high-cadence dynamic cycling against other forms of exercise or standard care. Future studies should include a control group to strengthen causal inferences regarding the effectiveness of high-cadence dynamic cycling in improving functional mobility in older adults with PD. Third, the walking distance used in our study was relatively short. Even though the literature suggests that reliability of IMU sensor based spatiotemporal gait parameter measurement from short walking bouts can be achieved by collecting at least three gait cycles[48], a walking distance during TUG test may not be sufficient. Previous studies have demonstrated that spatiotemporal gait parameters can be assessed during the TUG test using instrumented systems such as GAITRite in older adult populations[49]. Additionally, IMU-based approaches have shown that reliable spatiotemporal gait metrics can be derived from TUG test in populations with neurological disorders[50], supporting the feasibility of gait analysis during functional mobility tasks. Future studies should consider extending the walking distance to 10 meters. This would allow for capture of a greater number of valid gait cycles and thus provide a more comprehensive set of spatiotemporal gait parameters during walking. In addition, we plan to examine the changes in the affected and unaffected sides of older adults with PD and assess how these changes affect their level of gait asymmetry. These findings could be valuable in refining rehabilitation strategies tailored to the unique needs of this population. Lastly, we plan to directly measure cognition, independence, and quality of life in future studies. These measurements will evaluate how changes in spatiotemporal gait parameters resulting from high-cadence dynamic cycling influence these variables. This approach will provide a more comprehensive understanding of the benefits of high-cadence dynamic cycling on both gait parameters and broader functional outcomes. In addition, future studies should include larger sample sizes and randomized controlled trial (RCT) designs to improve statistical power and enhance the generalizability of the findings.

Conclusion

In conclusion, this study has shown that 12 sessions of high-cadence dynamic cycling can significantly improve spatiotemporal gait parameters in older adults with PD. In addition, we found that baseline MDS-UPDRS Motor III scores were significantly correlated with functional mobility, as measured by the TUG, and with several spatiotemporal gait parameters. This highlights the usefulness of spatiotemporal gait analysis as an effective tool for detecting and monitoring PD motor symptoms. Future research should aim to expand upon these findings with larger sample sizes with control group and longer walking distances to validate and extend our understanding of these effects. Additionally, exploring the asymmetrical changes in gait could provide deeper insights into tailored rehabilitation approaches for individuals with PD.

Ethics Approval

This study received ethical approval from the Kent State University IRB (Approval #087). This research was conducted ethically in

accordance with the World Medical Association Declaration of Helsinki.

Consent to Participate

All participants provided written informed consent prior to enrolment in the study.

Author's Contribution

Y.K: data collection, statistical analysis, writing- original draft. B.E.S: data collection, writing -review and editing. L.M.S: data collection, writing -review and editing. A.L.R: Study design, funding acquisition, project administrations and supervision, writing -review and editing. All authors read and approved the final version of the manuscript.

Funding

This work was funded by the Davis Phinney Foundation, TeCK Fund, the College of Education, Health, and Human Services at Kent State University and the Brain Health Research Institute at Kent State University, and US Department of Veteran's Affairs IO1RXO03676.

Acknowledgements

The authors would like to acknowledge Jessica Smith-Ricketts, Mason Hakeos, Jacob Herbst for assistance with data collection, Peter Gates and Prajakta Joshi for developing the entropy analysis code, and Hassan Abdar for building the dynamic bike.

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