Behshad Panjeh Zadeh [1]
Mahdi Majlesi [2*]
Ali Fatahi [1]
Hassan Safikhani [3]

THE EFFECT OF OBSTACLE CROSSING ON INTER-JOINT COORDINATION AND VARIABILITY IN GAIT OF INDIVIDUALS WITH PARKINSON'S DISEASE

VPLIV PREČKANJA OVIR NA MEDSKLEPNO KOORDINACIJO IN VARIABILNOST PRI HOJI POSAMEZNIKOV S PARKINSONOVO BOLEZNIJO

ABSTRACT

Understanding the impact of obstacle crossing on inter-joint coordination and variability in the gait of individuals with Parkinson's disease (PD) is critical for the development of effective rehabilitation strategies. The aim of this study was to investigate the effect of obstacle crossing on inter-joint coordination and variability in the gait of individuals with Parkinson's disease. A motion capture system recorded kinematic gait data in two conditions - normal gait and obstacle crossing - in 15 individuals with Parkinson's disease (8 males and 7 females) and 17 healthy age-matched controls (9 males and 8 females). The vector coding technique was employed to evaluate coordination and its variability for the Knee-Hip, Ankle-Hip, and Ankle-Knee joint pairs during gait and obstacle crossing. A significant difference was observed between the two groups in joint coupling angles during the loading response and push-off phases ($p < 0.05$). Obstacle crossing induced phase and coupling angle changes between joints in both groups ($p < 0.05$), but only in the PD group, it resulted in increased variability in the ankle-knee coupling angle during the push-off phase ($p < 0.05$). The PD group exhibited lower variability during normal gait and higher variability during obstacle crossing compared to the control group ($p < 0.05$). Parkinson's disease alters joint angles, leading to changes in joint coupling angles and phase coordination between joints. Moreover, the level of variability in joint coupling angles, particularly during the loading response and push-off phases, is influenced by Parkinson's disease.

Keywords: Parkinson's disease, Gait, Inter-joint coordination, Coupling angle, Variability

[1]***Department of Sports Biomechanics, Central Tehran Branch, Islamic Azad University, Tehran, Iran***

[2]***Department of Sport Biomechanics, Hamedan Branch, Islamic Azad University, Hamedan, Iran***

[3]***Department of Physical Education and Sport Sciences, Kermanshah Branch, Islamic Azad University, Kermanshah, Iran***

IZVLEČEK

Razumevanje vpliva prečkanja ovir na medsklepno koordinacijo in variabilnost pri hoji posameznikov s Parkinsonovo boleznijo (PB) je ključno za razvoj učinkovitih rehabilitacijskih strategij. Namen te študije je bil raziskati učinek prečkanja ovir na medsklepno koordinacijo in variabilnost hoje pri posameznikih s Parkinsonovo boleznijo. Sistem za zajem gibanja je beležil kinematične podatke o hoji v dveh pogojih – normalna hoja in prečkanje ovir – pri 15 posameznikih s Parkinsonovo boleznijo (8 moških in 7 žensk) ter 17 zdravih starostno usklajenih kontrolnih posameznikih (9 moških in 8 žensk). Tehnika kodiranja vektorjev je bila uporabljena za oceno koordinacije in njene variabilnosti pri parih sklepov koleno-kolk, gleženj-kolk in gleženj-koleno med hojo in prečkanjem ovir. Statistično pomembne razlike so bile ugotovljene med skupinama v kotih sklepnega povezovanja med fazama nalaganja in odriva ($p < 0,05$). Prečkanje ovir je povzročilo spremembe faz in kotov povezovanja med sklepi v obeh skupinah ($p < 0,05$), vendar je pri skupini PB povzročilo tudi povečano variabilnost v kotu povezovanja gleženj-koleno med fazo odriva ($p < 0,05$). Skupina s PB je kazala nižjo variabilnost med normalno hojo in višjo variabilnost med prečkanjem ovir v primerjavi s kontrolno skupino ($p < 0,05$). Parkinsonova bolezen spreminja kote sklepov, kar vodi do sprememb v kotih sklepnega povezovanja in fazni koordinaciji med sklepi. Poleg tega raven variabilnosti v kotih sklepnega povezovanja, zlasti med fazama kontakta in odriva, vpliva na posameznike s Parkinsonovo boleznijo.

Ključne besede: Parkinsonova bolezen, hoja, medsklepna koordinacija, kot povezovanja, variabilnost

Corresponding author:* Mahdi Majlesi

Department of Sport Biomechanics, Hamedan Branch, Islamic Azad University, Hamedan, Iran.
E-mail: majlesi11@gmail.com
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INTRODUCTION

Parkinson's disease (PD) is a prevalent and progressive neurological condition characterized by a combination of motor and non-motor symptoms that have detrimental effects on mobility, functional capabilities, and overall quality of life (Yang et al., 2020). The degeneration of dopaminergic neurons in the substantia nigra within the basal ganglia leads to a decrease in dopamine levels, a crucial neurotransmitter involved in movement regulation, thus resulting in the primary manifestations of PD (Poewe et al., 2017). Common motor symptoms observed in PD patients include bradykinesia, resting tremors, limb rigidity, and stooped posture, accompanied by an elevated risk of falls as the disease advances (Dennison et al., 2007). Various central physiological processes are affected in PD, impacting postural control and balance, such as diminished muscle strength and function, cognitive decline, a history of falls, and fear of recurring falls, all contributing to an increased susceptibility to falls (Fasano et al., 2017; Perera et al., 2018).

The human body can be viewed as a complex neural controller integrated with a nonlinear dynamic system (Scott Kelso et al., 1981), where movement variability may arise from disruptions in sensory input, neuromuscular control, and biomechanical factors (Kuo et al., 2021), as well as constraints from environmental, organismic, and task-related factors (Newell & Corcos, 1993). These variations can impact the body's dynamic system, potentially altering patterns of inter-joint coordination and variability, particularly during movements like walking. Stability and coordination are central themes in movement science; stability is defined by the system's resilience to minor perturbations, while coordination involves the alignment of multiple neural components to create stable movement patterns (Hof, 2008). In individuals with Parkinson's disease (PD), gait disturbances such as reduced limb coordination and increased step-to-step variability worsen as the disease progresses (Hausdorff et al., 1998; Hausdorff et al., 2015; Xue et al., 2023), increasing fall risk due to basal ganglia impairment, which is essential for rhythmic motor control (Hausdorff et al., 1998; Ma et al., 2022). PD also leads to cognitive deficits that affect movement planning and execution, impacting joint coordination during walking. Additionally, freezing of gait (FOG) poses a significant threat to stability in PD patients (Nanhoe-Mahabier et al., 2011, 2013).

Obstacle crossing and navigating through complex environments pose significant challenges in daily life and are identified as primary causes of falls among the elderly (Simieli et al., 2018) and PD patients (Gérin-Lajoie et al., 2006). Successful navigation necessitates planning and visual guidance (Patla & Greig, 2006) to adapt steps, typically occurring at least 6 steps before reaching the obstacle (Lythgo et al., 2007). Adjustments in walking involve modifying gait speed and increasing step-to-step variability as one approaches the obstacle, a trend that intensifies with age. Prior research indicates that older adults, due to heightened motor and sensory impairments associated with aging, elevate step height during obstacle negotiation and reduce walking speed to evade collisions with obstacles (Hausdorff et al., 1998; Ma et al., 2022; Nanhoe-Mahabier et al., 2011).

Studies involving Parkinson's patients also reveal that those who experience FOG even when they are medicated (in the ON state) exhibit greater variability in spatiotemporal parameters of gait and obstacle negotiation compared to those who do not experience FOG (Bloem et al., 2004; Kwon et al., 2024; Nantel et al., 2011). Some research findings indicate that the presence of obstacles along the walking path results in heightened step-to-step variability during walking (Lai et al., 2024; Lythgo et al., 2007). Conversely, certain studies have demonstrated a decrease in variability during obstacle crossing. In these cases, the reduction in gait speed, attributed to increased precision and safety in navigating obstacles, is cited as the cause of reduced variability (Hausdorff et al., 1998; Terrier & Schutz, 2003). Discrepancies between various studies can be attributed to differences in the severity of Parkinson's disease, medication ON or OFF periods, comorbidities, and the administration of psychotropic drugs, all of which influence study outcomes. Furthermore, tremors and involuntary movements in these patients may lead to instability and difficulty in positioning joints for obstacle negotiation (Stegemöller et al., 2012).

Based on the review of the research background and our information, no study was found that examines inter-joint coordination using the vector coding method in individuals with PD. Analyzing the inter-joint coordination pattern during gait can help identify factors involved in neuromuscular control and elucidate the role of risk factors in falls (Azadian et al., 2023b; Yen et al., 2009). Understanding disruptions in inter-joint coordination during gait and obstacle crossing is crucial for developing targeted rehabilitation strategies and technologies aimed at enhancing mobility and reducing fall risks in PD patients. Therefore, the objective of the current study is to investigate the impact of obstacle crossing on inter-joint coordination and its variability in the gait of individuals with PD. We hypothesize that obstacle crossing significantly affects the pattern of inter-joint coordination and variability at sagittal plane in individuals with PD.

METHODS

Participants

The total sample size was determined to be 24 individuals using G*Power software with a statistical power of 80%, a significance level of 0.05, and a minimum effect size of 0.24 (Kang, 2021). Fifteen patients with PD, comprising 8 males and 7 females, were recruited as the experimental group, while 17 healthy individuals, consisting of 8 females and 9 males, were selected as the control group (CG) using convenience sampling. The criteria for including individuals with Parkinson's disease (PD) included: a confirmed diagnosis of PD at stages II-III according to the Hoehn and Yahr scale (Hoehn & Yahr, 2001), being on medication during the ON phase (when the effects of levodopa are active), no history of implanted devices or deep brain stimulation, no orthopedic surgeries on the lower limbs within the last six months, and having intact visual and auditory systems. For the control group (CG), the inclusion criteria were: no prior experience with exercise, no significant surgical history, and no conditions impacting gait, such as neurological or musculoskeletal disorders. Additionally, the CG participants were required to have healthy vestibular, visual, and auditory systems. Both groups consisted of individuals aged between 50 and 70 years who could walk independently without the use of assistive devices.

Exclusion criteria included lower limb injuries or orthopedic problems in the past six months, severe arterial or orthopedic issues, acute heart diseases, significant blood pressure fluctuations, and mental weakness (Gazibara et al., 2014). This study received approval from the Ethics Committee of the Islamic Azad University, Hamedan Branch, under the ethical code 001.1401.IR.IAU.H.REC, and written informed consent was obtained from all participants before their participation in the study.

To evaluate the mental status and cognitive function as part of the inclusion criteria, we utilized the Mini-Mental State Examination (MMSE) questionnaire for both groups (total score of ≥20 points), to ensure adequate cognitive capacity for participation. Additionally, individuals with PD completed the Montreal Cognitive Assessment (MoCA) with a cut-off score of 13 (Kim et al., 2016) and the Parkinson's Disease Quality of Life Questionnaire (PDQL) to assess cognitive function and quality of life specific to PD. These assessments were used to ensure participants met the necessary cognitive and functional criteria for the study.

Instrumentation and procedures

Motion analysis was conducted utilizing a three-dimensional motion capture system (Vicon, Vicon Peak, Oxford, UK) equipped with six T20 series cameras operating at a frequency of 100 Hz. The lower limb movements of the participants were captured using spherical markers with a diameter of 14 millimeters, affixed to specific anatomical landmarks of both legs, following the Plug-In Gait marker set model (Vicon Peak, Oxford, UK)(Ferrari et al., 2008). Additionally, gait phase detection was captured using two Kistler force plates (Type 9281, Kistler Instrument AG, Winterthur, Switzerland) synchronized with the cameras, sampled at a frequency of 1000 Hz.

To ensure that each participant exhibited natural gait characteristics during testing, a familiarization session lasting 10 minutes was included (Lockhart et al., 2003). Subjects were instructed to ambulate along the walkway at self-selected speed, negotiating the force plates. The starting position was adjusted during initial trials to ensure the subjects' right foot was positioned over the first force plate, and the left foot over the second. Six trials were conducted, and from these, three successful trials were chosen for subsequent analysis.

In this study, participants were assigned two tasks: A) normal gait, and B) normal gait with obstacle crossing. The obstacle utilized in this research was a white, flexible foam plastic (15 cm height × 60 cm width × 6 cm depth), placed in the center of the calibrated space (Ambike et al., 2021).

Similarly, the kinematic data underwent filtration using a zero-lag fourth-order low-pass Butterworth filter with a cut-off frequency of 6 Hz (Jafarnezhadgero et al., 2020). Nexus software (Vicon Motion Systems, Oxford, UK) was used for synchronizing kinematic and ground reaction force data. The gait cycle was divided into distinct phases in sagittal plane: loading response phase (0–20% of the gait cycle), mid-stance (20–47% of the gait cycle), push-off (47–70% of the gait cycle), and swing phase (70–100% of the gait cycle) (Robertson et al., 2013). Each stride's data were normalized to comprise 100 data points using linear interpolation.

Vector coding was employed to calculate the inter-joint coordination. For each instant (i) during the stance phase, the coupling angle (γi) was calculated based on the consecutive proximal segmental angles (θP(i), θP(i+1)) and consecutive distal segmental angles (θD, θD(i+1)) according to Eqs. 1) and 2):

1) $$\gamma_i = Atan\left(\frac{\theta_{D(i+1)} - \theta_{Di}}{\theta_{p(i+1)} - \theta_{pi}}\right) \cdot \frac{180}{\pi}\, \theta_{p(i+1)} - \theta_{pi} > 0$$

2) $\gamma_{i = Atan\left(\frac{\theta_{D(i+1)} - \theta_{Di}}{\theta_{p(i+1)} - \theta_{pi}}\right). \frac{180}{\pi} + 180\ \theta_{p(i+1)} - \theta_{pi} < 0}$

The following conditions 3) were applied:

$$\theta_i = \begin{cases} \theta_i = 90\ \theta_{P(i+1)} - \theta_{Pi} = 0\ and\ \theta_{D(i+1)} - \theta_{Di} > 0 \\ \theta_i = -90\ \theta_{P(i+1)} - \theta_{Pi} = 0\ and\ \theta_{D(i+1)} - \theta_{Di} < 0 \\ \theta_i = -180\ \theta_{P(i+1)} - \theta_{Pi} < 0\ and\ \theta_{D(i+1)} - \theta_{Di} = 0 \\ \theta_i = Undefined\ \theta_{P(i+1)} - \theta_{Pi} = 0\ and\ \theta_{D(i+1)} - \theta_{Di} = 0 \end{cases} \quad (3)$$

Coupling angle (γi) was corrected to present a value between 0° and 360° according to 4) (Sparrow et al., 1987).

$$\gamma_i = \begin{cases} \gamma_i + 360\ \gamma_i < 0 \\ \gamma_i\ \gamma_i \ge 0 \end{cases} \quad (4)$$

Due to directional nature of coupling angle, the average coupling angle (γi) were calculated based on the average horizontal (xi) and vertical (yi) components at each instant using circular statistics (Azadian et al., 2023a; Jafarnezhadgero et al., 2020).

5) $\bar{x}_i = \frac{1}{n} \sum_{i=1}^{n} \cos \gamma_i$

6) $\bar{y}_i = \frac{1}{n} \sum_{i=1}^{n} \sin \gamma_i$

The following 7) were applied to correct the average coupling angle (γi) to present a value between 0° and 360°.

$$\bar{\gamma}_i = \begin{cases} Atan\left(\frac{\bar{y}_i}{\bar{x}_i}\right) \cdot \frac{180}{\pi}\ x_i > 0. y_i > 0 \\ Atan\left(\frac{\bar{y}_i}{\bar{x}_i}\right) \cdot \frac{180}{\pi} + 180\ x_i < 0 \\ Atan\left(\frac{\bar{y}_i}{\bar{x}_i}\right) \cdot \frac{180}{\pi} + 360 x_i > 0. y_i < 0 \\ 90\ x_i = 0. y_i > 0 \\ -90\ x_i = 0. y_i < 0 \\ indefined\ x_i = 0. y_i > 0 \end{cases} \quad (7)$$

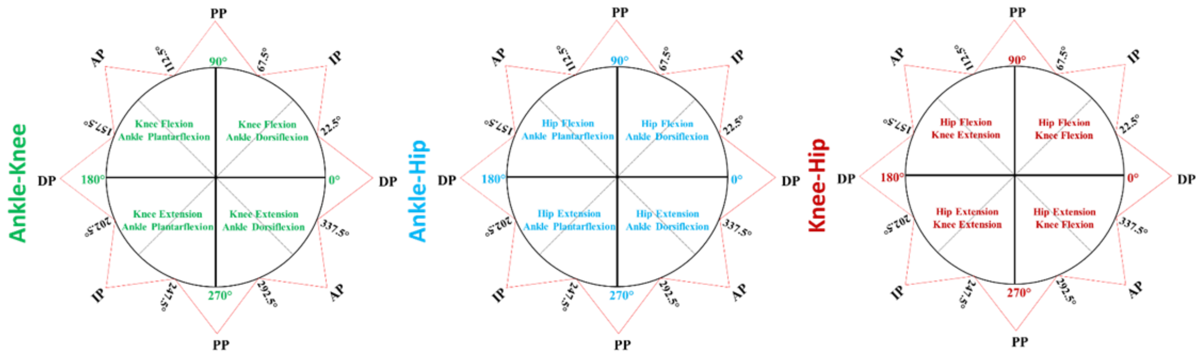
The length of average coupling angle ri was calculated according to 8)

8) $\bar{r}_i = \sqrt{\bar{x}_i^{\,2} + y_i^{\,2}}$

Coupling angle variability (CAV) was calculated according to 9)

9) $CAV_i = \sqrt{2(1 - \bar{r}_i)}\ \frac{180}{\pi}$

Figure 1 illustrates what a coupling angle indicates when it falls onto each of the quadrants.



Notes. A coupling angle of 0° or 180° indicates distal joint motion without proximal joint motion. A coupling angle of 90° or 270° indicates proximal joint motion without distal joint motion. A vector angle of 45°, 135°, 225°, and 315° indicates equal relative motion between the proximal and distal joints (Azadian et al., 2023b). Note: PP: proximal phase; DP: distal phase; AP: anti-phase; IP: in-phase.

Figure 1. Relationship between phase angle in each quadrant and distal-proximal joints' relative motion.

Statistical analyses

Statistical analysis was performed using SPSS software (version 21.0; SPSS Inc., Chicago, IL, USA) at a significance level of P<0.05 throughout all stages. The Shapiro–Wilk test was used to assess the normality of the outcome measures. Descriptive statistics were computed for all the demographic and outcome measures. As the data for balance variables had a normal distribution, parametric statistics were utilized for analysis. The experimental design of this study included three within-group factors: A) task with two levels (normal gait, obstacle crossing), B) gait phases with 4 levels (loading response, mid-stance, push-off, swing phases), and body side with two levels (right foot, left foot). Additionally, a between-group factor was considered, comprising two levels (PD group and control group). For within-group comparisons, repeated measures ANOVA was applied, while MANOVA was utilized for between-group comparisons. Demographic variables between groups were compared using the independent sample T-test.

RESULTS

The results of comparing demographic information indicated no significant differences between the groups, except for the MMSE test, which showed a significant difference (Table 1).

Table 1. Baseline characteristics in the control and PD groups.

	Groups		Sig.
	PD	**Control**	
N (female, male)	15 (7,8)	17 (8,9)	
Age (year)	61.60±6.23	60.52±6.17	0.62
Mass (Kg)	67.60±10.56	68.88±11.60	0.75
Height (cm)	1.64±0.10	1.64±0.09	0.86
BMI	25.13±3.39	25.71±3.45	0.64
MMSE	23.00±3.74	27.07±2.40	0.002
MoCa	22.80±3.14	NA	
PDQL	112.40±12.63	NA	

Notes. Values are mean ± standard deviation. Abbreviations: PD, Parkinson's disease; N, number of participants; BMI, body mass index; MMSE, Mini-Mental State Examination; MoCa, Montreal Cognitive Assessment; PDQL, Parkinson's disease quality of life; NA, not applicable. * Significance level p< 0.05.

Inter-joint coordination

Ankle-hip coupling

The results indicate a significant difference in ankle-hip coupling angle between the two groups during normal gait in the loading response and swing phases, as well as during obstacle crossing in the loading response phase (Table 2). Factor analysis revealed that the task factor did not significantly affect the ankle-hip coupling angle (FPD=0.242, pPD=0.631, FCG=0.541, pCG=0.475), but the interaction between task and gait phases was significant (FPD=10.10, pPD=0.000, FCG=3.56, pCG=0.023). The means demonstrated that obstacle crossing caused a change in the coordination phase during the push-off and swing phases, with no significant impact on other phases compared to normal gait.

Ankle-knee coupling

The difference in coupling angle and coordination phase between the two groups during both normal gait and obstacle crossing in the loading response phase was significant (Table 2). Factor analysis results indicated a significant effect of the task factor on the coupling angle of these joints in both groups (FPD=29.9, pPD=0.000, FCG=8.67, pCG=0.011). The means demonstrate that obstacle crossing resulted in a decrease in the coupling angle for both groups. Additionally, the investigation into the interaction between task and gait phases in these joints was also significant (FPD=15.75, pPD=0.000, FCG=15.1, pCG=0.000). Comparison of the means revealed that obstacle crossing had the most substantial impact on the coupling angle during the push-off phase, with a consistent effect observed in both groups. This led to a transition in the coordination pattern from in-phase to distal phase compared to normal gait.

Knee-hip coupling

The findings revealed a significant difference between the two groups concerning the coupling angle during normal gait, including loading response, mid-stance, and push-off phases, along with obstacle-crossing instances during the loading response phase (Table 2). Factor analysis showed that the interaction between task and gait phases was only significant in the PD group (FPD=5.04, pPD=0.005, FCG=2.50, pCG=0.073). The means indicated that in the PD group, obstacle crossing led to a change in the coupling angle and coordination phase during the mid-stance phase compared to normal gait.

Table 2. Coupling angle (mean ± standard deviation) in each sub-phase of gait in PD and Control groups.

	Sub-phase		**PD**				**CG**				**Between group in normal gait (p-value)**	**Between group in OBS gait (p-value)**
		foot	**Normal gait**		**OBS**		**Normal gait**		**OBS**			
Ankle-hip	LR	Left	270.08±58.30	PP	302.03±17.08	PP	268.34±42.37	PP	267.99±30.03	PP	0.929	**0.001**
		Right	291.87±18.57		283.30±28.73		271.09±13.23		256.94±27.52		**0.002**	**0.020**
	MS	Left	283.60±13.71	PP	274.60±14.90	PP	275.50±14.77	PP	30.16±260.34	PP	0.145	0.125
		Right	379.46±16.66		272.19±13.98		276.40±13.62		259.61±40.28		0.599	0.280
	PO	Left	116.02±21.34	AP	100.67±23.74	PP	114.57±13.24	AP	106.16±36.44	PP	0.797	0.640
		Right	116.86±20.41		104.57±23.87		119.36±17.93		115.97±36.28		0.733	0.335
	S	Left	150.96±15.72	AP	168.79±19.26	DP	145.39±21.82	AP	162.85±21.41	DP	0.446	0.448
		Right	153.90±20.83		165.74±20.10		138.01±18.65		161.86±24.89		**0.043**	0.654
Ankle-knee	LR	Left	110.21±20.57	PP	104.19±32.15	PP	134.49±26.23	AP	152.35±29.18	AP	**0.036**	**0.000**
		Right	106.62±19.87		106.91±26.51		145.82±20.24		154.01±26.63		**0.000**	**0.000**
	MS	Left	137.74±24.95	AP	146.16±26.70	AP	145.78±18.83	AP	155.64±18.84	AP	0.345	0.288
		Right	137.07±25.93		144.25±22.162		141.47±37.48		156.58±30.50		0.667	0.232
	PO	Left	217.43±37.70	IP	175.57±54.47	DP	225.93±26.74	IP	184.61±53.83	DP	0.498	0.662
		Right	229.66±35.41		192.46±47.00		231.55±35.89		192.44±61.42		0.890	0.999
	S	Left	182.81±10.47	DP	181.89±16.05	DP	186.56±11.19	DP	180.35±16.12	DP	0.368	0.802
		Right	181.05±13.37		180.98±11.02		184.62±9.51		177.05±12.06		0.423	0.377
Knee-hip	LR	Left	252.36±46.62	PP	280.17±22.55	PP	266.62±35.45	PP	251.61±26.77	PP	0.368	**0.042**
		Right	281.98±22.98		262.08±20.60		262.24±25.54		253.44±42.44		**0.041**	0.499
	MS	Left	262.92±15.39	PP	245.52±21.86	IP	250.58±17.40	PP	231.44±30.02	IP	**0.049**	0.168
		Right	257.33±21.61		243.33±23.16		252.93±12.04		235.39±37.73		0.591	0.508
	PO	Left	48.22±16.61	IP	53.54±18.03	IP	43.35±11.86	IP	57.79±33.03	IP	0.380	0.676
		Right	55.53±19.27		50.77±13.17		43.66±11.74		53.90±31.54		**0.047**	0.735
	S	Left	176.42±13.84	DP	178.45±31.21	DP	175.82±21.97	DP	16.58±175.12	DP	0.932	0.562
		Right	182.49±11.66		180.30±9.53		174.06±17.40		175.35±7.90		0.144	0.147

Notes. The sub-phases are categorized into the following gait events Loading Response (LR; 0–20% of gait cycle), Mid Stance (MS; 20–47% of gait cycle), Push-off (PO; 47–70% of gait cycle) and swing (S; 70-100% gait cycle). Unit for the values is degrees; OBS: Obstacle crossing; PP: proximal phase; DP: distal phase; AP: anti-phase; IP: in-phase; PD: Parkinson's disease; CG: control group.

Variability in Inter-Joint Coordination Pattern

Ankle-hip Inter-Joint Coordination Variability

The results revealed that the variability in ankle-hip coupling angle during normal gait was almost similar in both groups. However, during obstacle crossing, the variability in the CG showed a significant increase compared to the PD group in most gait phases (Table 3). Factor analysis indicated that the task factor (FPD=1.45, pPD=0.251, FCG=1.38, pCG=0.261) and the interaction between task and gait phases (FPD=1.91, pPD=0.144, FCG=0.331, pCG=1.17) had no effect on the ankle-hip coupling angle variability.

Ankle-knee Inter-Joint Coordination Variability

Table 3 illustrates the variability in ankle-knee coupling angle between the two groups. In both gait conditions, the CG demonstrated greater variability during the loading response phase and lesser variability during the push-off phase compared to the PD group. Factor analysis results indicated that the task factor did not significantly affect the variability of ankle-knee coupling angle in either group (FPD=1.73, pPD=0.211, FCG=1.69, pCG=0.215). The assessment of the interaction between task and gait phases was only significant in the PD group (FPD=7.66, pPD=0.000, FCG=1.32, pCG=0.28). Comparison of the means revealed that in the PD group, obstacle crossing significantly reduced variability during the loading response phase and increased it during the push-off phase.

Knee-hip Inter-Joint Coordination Variability

The analysis of differences in knee-hip coupling angle variability between the two groups indicated that during normal gait, the variability in the mid-stance and push-off phases was significantly higher in the PD group compared to the CG. Similarly, during obstacle crossing, the variability in the mid-stance and push-off phases was significantly higher in the CG than in the PD group (Table 3). The results of the factor analysis revealed that neither the task factor nor the interaction between task and gait phases were statistically significant (p>0.05).

Table 3. Coupling angle variability (mean ± standard deviation) in each sub-phase of gait in PD and Control groups.

	Sub-phase	foot	PD Normal gait	PD OBS	CG Normal gait	CG OBS	Between group in normal gait (p-value)	Between group in OBS gait (p-value)
Ankle-hip	LR	Left	21.62±11.96	12.53±6.75	25.23±34.03	23.02±20.97	0.735	**0.022**
		Right	26.48±12.11	31.02±12.56	21.01±9.70	30.03±15.28	0.421	0.939
	MS	Left	10.76±6.49	12.91±1.68	15.56±9.69	19.18±5.09	0.725	**0.031**
		Right	11.97±16.05	14.98±4.51	10.62±4.52	20.71±2.05	0.278	**0.042**
	PO	Left	11.81±7.45	16.26±4.31	11.98±4.53	24.56±6.64	0.953	**0.032**
		Right	14.32±5.54	16.96±11.29	13.33±7.82	31.74±9.12	0.701	**0.045**
	S	Left	10.80±4.36	22.22±8.06	15.91±10.47	16.05±10.61	0.166	0.163
		Right	16.26±8.43	21.76±16.07	16.83±9.25	22.76±10.34	0.912	0.868
Ankle-knee	LR	Left	18.47±13.81	16.27±10.26	30.67±12.70	26.37±11.49	**0.035**	**0.044**
		Right	24.41±11.51	16.32±10.53	29.50±13.51	32.43±12.81	0.293	**0.009**
	MS	Left	12.91±8.66	15.25±10.76	19.95±18.95	18.10±16.66	0.217	0.596
		Right	15.7±10.79	18.55±9.59	14.83±10.71	19.54±22.65	0.825	0.882
	PO	Left	25.97±10.65	51.56±14.15	24.10±10.89	34.72±12.94	0.769	**0.031**
		Right	35.26±12.53	52.18±10.74	26.91±9.42	39.09±8.73	**0.040**	**0.044**
	S	Left	13.38±10.48	11.11±5.44	10.69±3.44	18.84±10.94	0.421	0.081
		Right	13.74±7.51	12.54±7.11	10.90±4.02	11.92±6.57	0.223	0.813
Knee-hip	LR	Left	33.69±14.03	23.87±10.46	28.89±24.09	24.50±24.63	0.670	0.942
		Right	25.99±8.20	37.19±9.00	26.29±11.09	39.72±12.00	0.969	0.857
	MS	Left	14.18±9.78	15.52±6.81	20.13±8.92	24.73±5.53	0.396	**0.039**
		Right	15.88±6.55	21.76±8.01	17.92±10.35	25.24±13.66	0.698	0.816
	PO	Left	16.80±5.92	15.92±6.64	8.76±2.77	30.62±13.08	**0.040**	**0.032**
		Right	17.14±12.87	16.14±7.39	14.52±11.85	25.01±11.79	0.580	**0.050**
	S	Left	15.36±12.60	13.94±8.82	13.36±19.86	14.81±13.27	0.753	0.840
		Right	22.09±8.35	16.39±14.06	13.08±4.84	13.79±9.34	**0.042**	0.570

Notes. The sub-phases are categorized into the following gait events: Loading Response (LR; 0–20% of gait cycle), Mid Stance (MS; 20–47% of gait cycle), Push-off (PO; 47–70% of gait cycle) and swing (S; 70-100% gait cycle). Unit for the values is degrees; OBS: Obstacle crossing; PD: Parkinson's disease; CG: control group.

DISCUSSION

Understanding the inter-joint coordination and variability is crucial for unraveling the complexities of gait abnormalities and susceptibility to falls. In this study, we aimed to investigate the extent to which lower-limb inter-joint coordination and its variability differ during obstacle crossing between individuals with PD and healthy elderly subjects.

Analysis of inter-joint coordination

Ankle-hip coordination

The interaction between task and gait phases demonstrated that obstacle crossing led to a change in coordination phase during the push-off and swing phases. Both groups experienced a transition from an anti-phase to a proximal phase during push-off and from an anti-phase to a distal phase during the swing phase in normal gait. The push-off and swing phases in normal gait are in the anti-phase, involving hip flexion and plantar flexion at the ankle. Despite a significant difference in the amount of coupling angle between the two groups during normal gait and in the swing phase, the coordination phase in both groups was similar. However, obstacle crossing during the push-off phase led to the creation of a proximal phase, indicating hip flexion and no movement at the ankle joint. Obstacle crossing during the swing phase also resulted in the creation of a distal phase, signifying ankle plantar flexion and no movement at the hip. Therefore, both groups reduce the likelihood of obstacle collision by altering their coordination pattern during obstacle crossing. The observed changes in inter-joint coordination during obstacle crossing suggest that both groups employ adaptive mechanisms in motor control. This indicates that both individuals with Parkinson's disease and healthy controls modify their movement strategies to enhance stability and reduce collision risk. However, while both groups adopt adaptive coordination patterns, individuals with PD may exhibit less effective motor control compared to controls, leading to different movement dynamics (Stegemoller et al., 2012).

Ankle-knee coordination

The difference between the two groups in both the ankle-knee coupling angle and coordination phase was significant in both normal gait and obstacle crossing conditions during the loading response phase. The coordination phase during the loading response was anti-phase in the CG and proximal phase in the PD group. Two reasons can be cited for this: first, the gait speed in the CG was significantly higher, leading them to traverse the proximal phase more quickly. Second, staying longer in the proximal phase is essential for maintaining balance and gait stability (Harbourne & Stergiou, 2009), indicating longer double support during the loading response phase. Longer double support is indicative of balance deficits in individuals with PD during normal gait or obstacle crossing. Due to the presence of obstacles, individuals with PD face challenges related to balance, which can lead to reduced speed and consequently alter their movement phases. Overall, the task factor led to a change in ankle-knee coupling angle and coordination phase in both groups. Analyzing the gait phases in both groups showed that obstacle crossing had the most significant impact on the coupling angle during the push-off phase. According to the results of this study, the ankle-knee joints are in the same phase during the push-off phase and normal gait, but obstacle crossing caused a transition to the distal phase. Previous studies have shown that distal joint movements indicate precision in walking (Chiu et al., 2013; Ghanavati et al., 2014); therefore, transitioning to the distal phase and utilizing it in the presence of an obstacle seems logical.

Knee-hip coordination

Although there was a similar movement phase between the two groups, the CG exhibited a significantly lower coupling angle in certain stages of normal gait. Factor analysis revealed a notable interaction between task and gait phases. Examination of the means demonstrated that obstacle crossing resulted in a shift in the coupling angle and coordination phase during the mid-stance phase compared to normal gait, a phenomenon observed in both groups. During normal gait, a proximal phase was observed in the mid-stance phase, indicating hip movement and knee immobility. However, during obstacle crossing in this phase, the hip and knee were in-phase (both extending), suggesting that encountering an obstacle in the movement path could trigger early knee joint movement to navigate the obstacle. This suggests that knee-hip coordination during obstacle crossing is less affected by PD, whereas the ankle-knee coordination shows more pronounced effects. The simultaneous extension of the hip and knee joints during obstacle crossing likely results from a biomechanical adaptation to ensure effective clearance and stability. This in-phase movement allows for better control of the center of mass, which is crucial for maintaining balance while overcoming obstacles.

Analysis of inter-joint coordination variability

The findings concerning variability in coupling angles revealed that during normal gait, the PD group demonstrated higher variability compared to the CG. However, during obstacle crossing, the CG exhibited increased variability relative to the PD group. This suggests that when faced with an obstacle, the CG significantly augmented the variability in joint coupling angles compared to the PD group. According to complexity theory, the optimal level of variability for optimal performance follows an U-shaped relationship (Stergiou et al., 2013). Deviation from this optimal state leads to a system that is more predictable, rigid, and exhibits robotic motor-like behavior (Vermeulen, 2021). Going beyond the optimal state introduces noise and unpredictability into the system, disrupting flexibility and adaptability in both scenarios (Stergiou et al., 2006; Stergiou et al., 2013). Consequently, one may infer that an increase in variability during obstacle crossing in the CG reflects adaptability and adjustment to new conditions (Hamill et al., 1999). Specifically, the substantial increase in variability during the loading response and push-off phases may suggest an elevated requirement for these phases to adapt to various environmental conditions.

Comparison between normal gait and obstacle crossing in the PD group revealed that obstacle crossing resulted in decreased variability in the ankle-knee coupling angle during the loading response phase and increased variability during the push-off phase compared to normal gait. This suggests that PD patients employ two strategies for safety and stability while crossing obstacles: reducing variability by limiting joint movements and adopting a proximal movement pattern. The decrease in walking speed and reduction in variability align with symptoms of the disease in this group, such as bradykinesia, hypokinesia, or rigidity, respectively (von der Recke et al., 2023). The findings revealed an increase in variability in the ankle-knee angle during the push-off phase, especially in the PD group. This increase is statistically significant compared to both the CG and normal walking, suggesting a heightened risk of falls among PD patients during obstacle crossing (Pieruccini-Faria & Montero-Odasso, 2018).

Strengths and limitations

The limitations of the study include its focus on a specific age range, which may limit the generalizability of the findings to other age groups. Additionally, the experiments were conducted in a controlled laboratory setting, which may not fully reflect real-world conditions, potentially impacting motor performance in real-life environments. Furthermore, the study was cross-sectional, so long-term changes in joint coordination and gait patterns were not examined.

CONCLUSION

The findings of this research demonstrate the significant impact of PD on joint coordination and variability in joint coupling angles. The loading response and push-off phases exhibited higher sensitivity to PD compared to other phases of gait. The results also suggest that obstacle crossing influences joint coordination and variability in coupling angles, particularly resulting in increased variability during the push-off phase among PD patients, posing a potential risk factor for falls. Based on these findings, it is recommended that PD patients engage in balance exercises that emphasize maintaining single-leg balance or weight shifting.

Declaration of competing interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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