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ORIGINAL ARTICLE

Balance and biomechanics: exploring lower extremity biomechanics in Parkinson's disease

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Abstract

Background Postural instability (PI) is a symptom seen in 16% of Parkinson Disease (PD) patients and has limited response to dopaminergic therapy. Understanding the factors contributing to PI, such as biomechanical changes, is important for the development of non-pharmacological treatment.

Aims To investigate the relationship between lower extremity biomechanics and balance parameters in PD patients.

Methods A total of 18 participants ($n=9$ female) were enrolled in the study. Lower extremity biomechanics were evaluated using a combination of measurements, including femoral anteversion angle, Q angle, leg length, navicular drop test (NDT), gastrocnemius shortness, range of motion (ROM) assessments, and the Foot Posture Index (FPI). Balance was assessed through the Postural Stability Test, Fall Risk Index (FRI), and the Mini-BESTest.

Results A significant correlation was observed between FRI and femoral anteversion ($r=0.58$, $p=0.011$) as well as hip flexion ROM ($r=0.67$, $p=0.002$) and lateral malleoli curvature ($r=0.48$, $p=0.04$). Overall Stability Index (OSI) was significantly associated with NDT ($r=0.53$, $p=0.024$) and forefoot abduction/adduction ($r=0.67$, $p=0.002$). The Anteroposterior Stability Index (APSI) correlated with NDT ($r=0.47$, $p=0.048$), knee flexion ROM ($r=0.47$, $p=0.045$), and forefoot abduction/adduction ($r=0.65$, $p=0.004$). Moreover, Mini-BESTest scores were associated with hip abduction ($r=0.55$, $p=0.017$), ankle plantar flexion ($r=0.63$, $p=0.005$), and knee flexion ROM ($r=0.47$, $p=0.048$).

Conclusions This study demonstrated that lower extremity biomechanical features, including alignment and joint mobility, are significantly linked to balance and fall risk in individuals with PD. Incorporating biomechanical assessments into clinical evaluations may aid in developing individualized treatment strategies for balance disorders in PD.

Keywords Assessment · Balance · Biomechanics · Fall risk · Parkinson's disease · Postural instability

Introduction

Parkinson's disease (PD) is a chronic and progressive neurological disorder that develops as a result of degeneration of dopaminergic neurons located in the substantia nigra pars compacta region. Dopamine deficiency leads to impairment in motor functions and common symptoms including tremor, rigidity, bradykinesia, and postural instability (PI) [1]. PI occurs in 16% of patients, and its frequency increases as the disease progresses. In addition, it causes falls in approximately 60% of PD patients and hospitalization in 75%. PI has a limited response to dopaminergic therapy [2]. Therefore, it is important to understand the factors contributing to PI in order to develop non-pharmacological treatment strategies.

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Postural stability refers to maintaining the body's center of mass within the base of support and resisting factors that disrupt balance during movement [3]. It is a complex skill that requires the integration of various neural networks within the brain, achieved through the processing of information received from the peripheral and central nervous systems and the generation of appropriate outputs [4]. Therefore, motor dysfunctions in patients with PD negatively affect postural stability [5]. Various strategies, such as ankle, hip, squatting, and stepping mechanisms, are utilized to maintain balance during daily activities. These strategies function as unconscious mechanisms aimed at preventing falls. The effective execution of these mechanisms is closely related to the biomechanical alignment of the lower extremity [6, 7].

Postural deformities, ranging from flexion posture to conditions such as camptocormia, Pisa syndrome, and scoliosis, are observed in one-third of patients with PD. Increased flexion of the spine, in particular, triggers a series of biomechanical changes. Some of these changes include increased anterior pelvic tilt, femoral anteversion, *Q* angle, and alterations in foot posture. In addition to abnormal posture, motor symptoms such as rigidity and muscle strength imbalances also contribute to these biomechanical changes [7–9]. Therefore, assessing alignment of lower extremity in these patients may be crucial for postural stability.

In PD, problems such as rigidity, bradykinesia, and limitation in the range of motion of the lower extremity joints (hip, knee and ankle) occur due to motor dysfunction of the central nervous system [10]. Especially, range of motion (ROM) limitations in these joints can be very important for the proper exposure of ankle and hip strategies. Restrictions in joint mobility may not only contribute to postural instability but may also lead to festination (walking with fast and small steps) and decreased stride length. In patients with PD, gait disorders and changes in step length cause impaired stepping strategy, resulting in PI [11].

Considering all these aspects, a better understanding of lower extremity biomechanical changes in PD patients may contribute to the development of targeted treatment approaches (physiotherapy, exercise programs, assistive devices) aimed at improving balance. The aim of this study was to investigate the relationship between lower extremity biomechanics and balance parameters in PD patients.

Method

Participants

The present study was a cross-sectional and observational design. It was carried out between March and April 2025 at the Neurology Outpatient Clinic of Bezmialem Vakif University, with patients diagnosed with PD. Patients who voluntarily agreed to participate after being informed about the study were included. The study was conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent after being informed about the study, potential risks, and benefits. All assessments were carried out at the Neurological Rehabilitation Education and Research Laboratory, Department of Physiotherapy and Rehabilitation, Faculty of Health Sciences, Bezmialem Vakif University.

The inclusion criteria were (a) being 40 years of age or older, (b) having been diagnosed with PD by a specialist for at least one year and no change in the type or dosage of antiparkinsonian medication in the last six months, (c) having Hoehn and Yahr stage 1 to 3, and (d) having a Standardized Mini-Mental Test score above 23. The exclusion criteria were (a) visual or hearing impairment, (b) communication difficulties, (c) presence of any musculoskeletal condition that could affect balance performance, (d) recent participation in a rehabilitation program within the last six months, and (e) clinical instability of PD in the past month.

Sample size

The sample size and power calculation for our study were determined with the PS Power statistical programme according to the minimal clinically important difference (MCID) value of Mini BESTest, which was selected as the primary outcome measure for PD patients. The calculations were performed with a 95% confidence interval, MCID value of 3.4 and standard deviation value of 3.1, 80% power, and 0.05 significance level [12]. With these parameters, it was found that a sample of at least 15 patients should be formed. When a conservative fall rate of 20% was added, the total number of volunteers expected to participate in the study was determined as at least 18.

Outcome measures

Lower extremity biomechanics were assessed in all PD voluntary participants using femoral anteversion angle, *Q* angle, limb length measurement, navicular drop test, gastrocnemius tightness test, hip-knee-ankle joint ROM, and Foot Posture Index. Balance was evaluated using Biodex Balance System (BDS) and Mini-Balance Evaluation Systems Test (Mini-BESTest). All assessments were performed by the same physiotherapist. Evaluations were conducted during the "on" phase, when participants responded well to symptomatic treatment. Patients were instructed to take their medication at least one hour before testing to ensure assessments occurred during this period. To minimize fatigue-related effects, the UPDRS was administered by the referring physician during clinical examination. Active and passive

assessments (e.g., ROM evaluations and anthropometric measurements) were structured consecutively in the same position to reduce unnecessary repositioning. Additionally, 10-min rest intervals were provided between anthropometric assessments, Biodex Balance System tests, and the Mini-BESTest to ensure participant recovery.

The Unified Parkinson's Disease Rating Scale (UPDRS)

UPDRS was developed by combining elements from existing scales to provide a comprehensive, yet efficient and flexible tool for monitoring disability and impairment in Parkinson's disease. The final version, officially known as UPDRS version 3.0, was established after several trial versions. The scale consists of four parts with a total of 42 items, largely adapted from earlier tools and revised by a consortium of movement disorder specialists: Part I—Mentation, Behavior, and Mood (4 items); Part II—Activities of Daily Living (13 items); Part III—Motor Examination (14 items); and Part IV—Complications (11 items) [13]. The maximum scores for each section are as follows: Mentation, Behavior, and Mood—16 points, Activities of Daily Living—52 points, Motor Examination—108 points, and Complications—23 points, with a total possible score of 199 points. Higher scores indicate a worsening of the patient's clinical condition. The minimal clinically important difference (MCID) is 8 points [14]. The UPDRS is a valid and reliable tool in Turkish. The validity and reliability of the Turkish version were established by Akbostanci et al. [15]. In this study, the motor section of the UPDRS, known as UPDRS Part III (Motor Examination), was used to evaluate the severity of motor symptoms. This section consists of 14 items, each scoring between 0 and 4. The MCID for UPDRS-III has been reported as 5 points [14]. The section assesses various motor function, including speech, facial expression, rest tremor, postural tremor, rigidity, finger tapping, hand movements, rapid alternating hand movements, leg agility, arising from a chair, posture, gait, postural stability, and body bradykinesia and hypokinesia [13].

Patient Assessment Form

A Patient Assessment Form was used to record demographic and clinical data of participants with PD. It included information such as age, gender, dominant side, education, medical and family history, disease duration, treatment, and medication use.

Femoral anteversion

In the prone position, with the hip in neutral and the knee flexed at 90°, the greater trochanter was palpated manually. The hip was passively internally rotated until the greater trochanter reached its most lateral point. The angle between the tibial axis and a vertical reference line was then measured with a goniometer and recorded in degrees [16].

Q angle

The *Q* angle was measured using a universal goniometer while participants stood with equal weight on both feet. It was defined as the angle between the line from the anterior superior iliac spine (ASIS) to the center of the patella and the line from the center of the patella to the tibial tuberosity. The values were recorded in degrees [17].

Leg length

In the supine position, the ASIS and medial malleoli were marked, and the distance between them was measured with a measuring tape and recorded in centimeters. Equal lengths indicated no anatomical leg length discrepancy (recorded as negative [−]), while any difference was recorded as positive (+) [18].

Navicular drop test

This test is used to assess foot pronation by measuring how much the navicular bone moves when going from a neutral position to a relaxed standing position. It helps evaluate the flexibility of the medial longitudinal arch and navicular position. Participants sit with hips and knees at 90° and the subtalar joint in a neutral position, confirmed by palpating the talus for equal pressure on both sides. The navicular bone is then marked, and its height is measured with a digital caliper. After the participant stands with equal weight on both feet, the navicular height is measured again. The test's reliability (intraclass correlation coefficient (ICC)) ranges from 0.33 to 0.76 [19].

Gastrocnemius shortness test

In this test, the individual sits on a flat surface with legs fully extended and tries to reach their toes. If they can touch their toes, gastrocnemius muscle length is considered normal. Difficulty in dorsiflexing the foot suggests muscle shortness [18].

Hip-knee-ankle range of motion

Hip flexion–extension For hip joint flexion measurement, the subject was positioned in a supine position with the extremity to be measured in knee flexion, ensuring that lumbar lordosis was not increased. The pivot point of the goniometer was placed on the greater trochanter, with the stationary arm held parallel to the axilla. The moving

arm followed the lateral midline of the femur. The subject was asked to perform hip flexion actively and passively to the maximum possible range, and the measurement was recorded in degrees [18].

Hip abduction Hip abduction range of motion was measured in the supine position with the legs extended. The opposite hip was stabilized to prevent pelvic movement. The test leg was moved outward until pelvic motion began. A goniometer was placed with the stationary arm aligned between both ASIS points, the moving arm along the femur, and the fulcrum at the lateral aspect of the hip. The angle was recorded in degrees [18].

Knee flexion Knee flexion was measured in the prone position. The goniometer's pivot was placed on the lateral femoral condyle, with the stationary arm aligned with the femur and the moving arm along the fibula. The knee was flexed actively and passively to the maximum range, and the angle was recorded in degrees [18].

Ankle plantar-dorsiflexion Ankle dorsiflexion and plantarflexion were measured in the sitting position with relaxed knees. The neutral ankle position was set as 0°. A universal goniometer was used, with the pivot on the lateral malleolus, the stationary arm aligned with the fibula, and the moving arm aligned with the 5th metatarsal. The subject performed active and passive dorsiflexion and plantarflexion to the maximum range, and the angles were recorded in degrees [18, 20].

Foot Posture Index-6 (FPI-6)

The FPI-6 is a tool used to evaluate foot posture based on six criteria: palpation of the distal talus, observation of the submalleolar and supramalleolar curves, calcaneal alignment, navicular prominence, medial longitudinal arch height, and toe visibility. Each item is scored from −2 (supination) to +2 (pronation), and the total score reflects overall foot posture. The Turkish version of the FPI-6 showed excellent internal consistency (Cronbach's $\alpha = 0.85$ and 0.78), test–retest reliability ($ICC_{2,k} = 0.96$ and 0.94), and inter-rater reliability ($ICC_{2,k} = 0.93$ for both dominant and non-dominant limbs) [21, 22].

Biodex Balance System

Biodex Balance System (BBS) is a computerized device used to assess postural stability, limits of stability, and fall risk. It includes a movable platform with a 360° range of motion and adjustable tilt angles up to 20°, allowing difficulty levels from 1 (least stable) to 12 (most stable). The system has proven reliability and validity. Before testing, participants received instructions and were assessed barefoot, with eyes open and arms relaxed. Foot positions were standardized using reference points, and screen and arm support heights were adjusted individually. A trial run was given to reduce learning and fatigue effects. Two tests—postural stability and fall risk—were performed, with a 5-min rest in between. Both tests show excellent reliability in people with Parkinson's disease (ICC) > 0.90) [23, 24].

Postural Stability Test The Postural Stability Test measures a person's ability to maintain balance on a stable platform by tracking deviations from the center. It provides overall, anterior/posterior, and medial/lateral stability indices, with higher scores indicating poorer balance. The test lasted 30 s with a 15-s rest and was repeated three times [23, 24].

Fall Risk Index The Fall Risk Index measures balance by tracking deviations from the center as the surface shifts from stable to unstable. In this study, the platform level was set at 12–8 for all participants [23, 24].

Mini-Balance Evaluations Systems Test (Mini-BESTest)

Mini-BESTest is a valid and reliable tool for assessing balance in individuals with Parkinson's disease [25]. It includes 14 items across four areas: anticipatory postural adjustments, reactive control, sensory orientation, and dynamic gait. The test is scored out of 28, with higher scores indicating better balance. It takes about 10–15 min to complete and has high inter-rater and test–retest reliability, as well as strong validity compared to the BESTest [25, 26].

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics 27 (IBM, USA). The normality of data distribution was assessed with the Shapiro–Wilk test. Descriptive statistics were presented as mean ± standard deviation. Statistical comparisons between the right and left extremities were conducted using the paired samples *t*-test. The correlation between lower extremity biomechanics and balance parameters was analyzed using Pearson's correlation coefficient for parametric (normally distributed) data and Spearman's correlation coefficient for non-parametric data. Pearson's *r* values were interpreted as follows: very strong (0.90–1.00), strong (0.70–0.89), moderate (0.50–0.69), weak (0.30–0.49), and insignificant (0.00–0.29) (31, 32). Spearman's rho values were interpreted as very weak (0.00–0.19), weak (0.20–0.39), moderate (0.40–0.59), strong (0.60–0.79), and very strong (0.80–1.00) [27].

Table 1 Demographic characteristics of participants

N = 18	Mean ± SD or (Min–Max) or *n* (%)
Age (years) (min–max)	68.44 ± 7.59 (48–81)
Disease duration (years) (min–max)	3.50 ± 2.72 (1–9)
Gender	*n(%)*
Female	9 (%50)
Male	9 (%50)
Education level	*n(%)*
None	4 (%22.2)
Primary school	8 (%44.4)
High school	3 (%16.7)
University	2 (%11.1)
Postgraduate	1 (%5.6)
Medication use	*n(%)*
Less than 3 doses per day	3 (%16.8)
Three doses per day	11 (%61.1)
Four doses per day	4 (%22.2)
Initial symptom	*n(%)*
Resting tremor	11 (%61.1)
Bradykinesia	2 (%11.1)
Rigidity	1 (%5.6)
Speech disorder	1 (%5.6)
Balance disorder	2 (%11.1)
Depression	1 (%5.6)
Hoehn and Yahr stage	*n(%)*
1	3 (%16.6)
1.5	5 (%27.7)
2	6 (%33.3)
2.5	2 (%11.1)
3	2 (%11.1)
The Mini Mental State Examination (MMSE)	26.05 ± 1.55 (24–29)
UPDRS-III	17 ± 7.66 (5–30)

SD standard deviation; *min* minimum; *max* maximum; *n* number of cases; *n (%)* number of cases percentage; *UPDRS-III* The Unified Parkinson's Disease Rating Scale-Motor Examination

Results

Twenty-seven consecutive patients were screened for potential eligibility. Nine individuals were excluded from the study for personal reasons, including communication difficulties ($n = 2$), musculoskeletal conditions that could affect balance performance ($n = 3$), and recent participation in a rehabilitation program within the last six months ($n = 4$). The final sample consisted of 18 individuals ($n = 9$ female), with a mean age of 68.44 years (SD = 7.59; range: 48–80). All participants were unemployed, and their dominant side was the right. The mean disease duration was 3.50 ± 2.72 years. The participants' mean UPDRS-III score was 17 ± 7.66 (5–30), the mean Mini-BESTest score was 17.5 ± 5.8 (6–26) and the mean FPI-6 score was 3.05 ± 4.49. Demographic and clinical characteristics of the participants are reported in Table 1.

The correlation between femoral anteversion, navicular drop test, *Q* angle, leg length, gastrocnemius shortness, Mini-BESTest, and Biodex measurements of the participants is shown in Table 2 and Fig. 1. There is a strong correlation between left lower extremity femoral anteversion angle values and Fall Risk Index (FRI) ($r = 0.58$, $p = 0.011$). There is a strong correlation between the right side navicular drop test and OSI ($r = 0{,}53$, $p = 0.024$) and a moderate correlation between APSI ($r = 0.47$, $p = 0.048$).

The correlation between bilateral hip, knee, and ankle joint ROM values and Mini-BEST and Biodex balance measurement results are shown in Table 3 and Fig. 2. A strong significant correlation was found between hip flexion ROM values of the left lower extremity and FRI score ($r = 0.67$, $p = 0.002$). A strong significant correlation was found between hip abduction ROM values of the left lower

Table 2 Pearson's correlation coefficients between femoral anteversion, navicular drop, *Q* angle, leg length, shortness of gastrocnemius, and Biodex measurements

	Femoral anteversion		Navicular drop test		***Q*** **angle**		Leg length		Gastrocnemius shortness	
	R	L	R	L	R	L	R	L	R	L
Mean ± SD	11.67 ± 4.8	15.94 ± 7.2	1.2 ± 0.6	0.9 ± 0.6	13.3 ± 5.4	16.8 ± 9.6	82.13 ± 4.5	81.72 ± 5.3	–	–
OSI	−0.33	0.14	**0.53***	0.29	−0.19	−0.15	0.20	0.18	−0.14	−0.04
APSI	−0.30	0.08	**0.47***	0.28	−0.12	−0.12	0.12	0.10	−0.14	−0.05
MLSI	−0.21	0.39	0.53	0.17	−0.33	−0.25	0.43	0.41	−0.03	0.05
FRI	−0.22	**−0.58***	0.24	−0.01	0.04	0.26	0.16	0.04	0.2	0.14
MBT	0.01	0.15	−0.16	−0.18	−0.11	−0.30	−0,36	−0,28	−0.14	−0.06
p	0.043		0.232		0.046		0.328		0.331	

Pearson's correlation analysis

SS standard deviation; *OSI* Overall Stability Index; *MLSI* Mediolateral Stability Index; *APSI* Anteroposterior Stability Index; *R* right; *L* left; *FRI* Fall Risk Index; *MBT* Mini-BESTest; *p* paired samples test

*$p < 0.05$; *p* values represent the statistical significance of the difference between right and left limbs

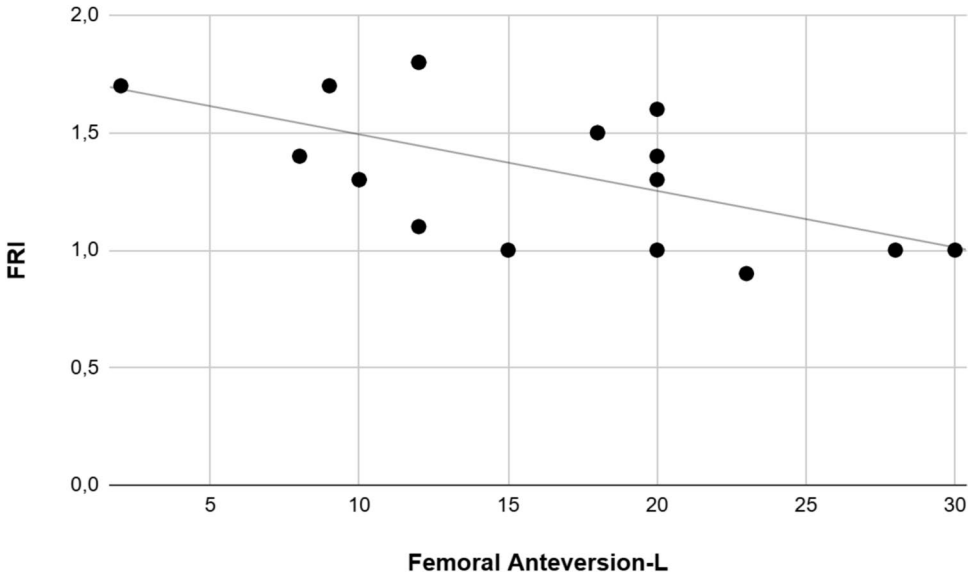

Fig. 1 Correlation between the Fall Risk Index and femoral anteversion angle

Table 3 Pearson's correlation coefficients between hip, knee, ankle joint range of motion values and Biodex measurements

	Mean ± SD	OSI	APSI	MLSI	FRI	MBT	*p
Hip flexion-R	100.39 ± 18.3	−0.20	−0.19	−0.14	0.19	0.16	0.031
Hip flexion-L	110.44 ± 22.6	−0.09	−0.08	−0.12	**0.67***	−0.19	
Hip abduction-R	33.28 ± 11	−0.09	−0.06	−0.09	−0.07	0.43	0.001
Hip abduction-L	39 ± 9.9	−0.13	−0.13	−0.03	−0.11	**0.55***	
Knee flexion-R	104.67 ± 16.6	−0.03	−0.04	0.08	0.42	0.12	0.269
Knee flexion-L	99.89 ± 17.2	−0.41	**−0.47***	0.10	−0.07	**0.47***	
Plantar flexion-R	23.61 ± 9.4	−0.21	−0.19	−0.09	−0.37	**0.63***	0.550
Plantar flexion-L	24.67 ± 9.3	−0.18	−0.18	−0.02	−0.14	0.28	
Dorsi flexion-R	15.44 ± 6.3	0.09	0.13	−0.05	−0.01	−0.02	0.038
Dorsi flexion-L	12.39 ± 5.8	−0.01	0.05	−0.15	−0.21	0.02	

Pearson's correlation analysis

SS standard deviation; *OSI* Overall Stability Index; *MLSI* Mediolateral Stability Index; *APSI* Anteroposterior Stability Index; *R* right; *L* left; *FRI* Fall Risk Index; *MBT* Mini-BESTest; *p* paired samples test

*$p < 0.05$; *p* values represent the statistical significance of the difference between right and left limbs

extremity and Mini-BESTest score ($r = 0.55$, $p = 0.017$). A moderate significant correlation was found between knee flexion ROM values of the left lower extremity and APSI score ($r = 0.47$, $p = 0.045$) and Mini-BESTest score ($r = 0.47$, $p = 0.048$). A strong significant correlation was found between plantar flexion ROM values of the left lower extremity and Mini-BESTest score ($r = 0.63$, $p = 0.005$).

The correlation between bilateral lower extremity Foot Posture Index (FPI-6) scores, Mini-BESTest, and Biodex measurements of the individuals participating in the study is shown in Table 4. There was a strong and significant correlation between the right lower extremity forefoot abduction/adduction position and OSI ($r = 0.67$, $p = 0.002$) and APSI ($r = 0.65$, $p = 0.004$). In addition, there was a moderate significant correlation between FRI and supra and infra lateral malleoli curvature in the left lower extremity forefoot ($r = 0.48$, $p = 0.04$).

Discussion

The findings of this study suggest that lower extremity biomechanical factors are significantly associated with balance performance and fall risk in individuals with PD. Among alignment-related variables, femoral anteversion, navicular drop, and FPI-6 demonstrated notable correlations with postural stability parameters. Similarly, limitations in joint range of motion—particularly hip flexion, hip abduction, knee flexion, and ankle plantarflexion—were found to be linked to both static and dynamic balance impairments.

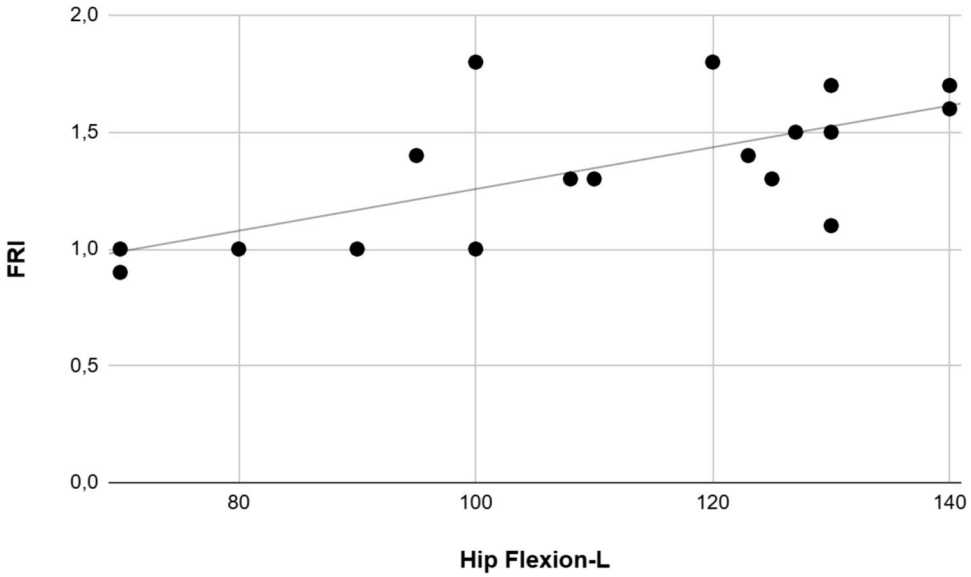

Fig. 2 Correlation between the Fall Risk Index and hip joint range of motion

Table 4 Pearson's correlation coefficients between Foot Posture Index and Biodex measurements

	FPI-1		FPI-2		FPI-3		FPI-4		FPI-5		FPI-6		FPI Total	
	R	L	R	L	R	L	R	L	R	L	R	L	R	L
OSI	0.04	0.03	0.30	0.17	−0.14	−0.12	−0.29	−0.09	−0.35	−0.19	**0.67***	0.24	0.004	−0.47
APSI	0.08	0.03	0.35	0.23	−0.15	−0.11	−0.21	−0.09	−0.33	−0.10	**0.65***	0.21	0.07	−0.005
MLSI	−0.01	−0.07	−0.00	−0.06	−0.05	−0.13	−0.37	−0.04	−0.23	−0.36	0.29	0.32	−0.21	−0.11
FRI	−0.23	−0.08	0.11	**0.48***	−0.18	−0.11	0.17	0.16	−0.06	0.04	−0.24	0.14	0.35	0.24
MBT	−0.41	−0.07	−0.06	−0.01	−0.25	−0.20	−0.02	−0.12	−0.32	−0.22	−0.05	−0.32	−0.45	−0.34
***p**	0.430		0.430		0.056		1.00		0.269		0.749		0.274	

Pearson's correlation analysis

OSI Overall Stability Index; *MLSI* Mediolateral Stability Index; *APSI* Anteroposterior Stability Index; *FRI* Fall Risk Index; *R* right; *L* left; *FPI* Foot Posture Index; *FPI-1* rearfoot talar head palpation; *FPI-2* supra and infra lateral malleoli curvature; *FPI-3* calcaneal position; *FPI-4* prominence in the region of the talonavicular joint; *FPI-5* congruence of the medial longitudinal arch; *FPI-6* abduction/adduction on forefoot; *MBT* Mini-BESTest; *p* paired samples test

*$p < 0.05$; *p* values represent the statistical significance of the difference between right and left limbs

These results support the hypothesis that peripheral musculoskeletal changes are associated with the postural instability commonly observed in PD and complement the central motor deficits typically highlighted in the literature.

The association between lower limb alignment and fall risk appears to be of minimal importance but may be important considering the multifactorial nature of falls. Femoral anteversion, which indicates rotational alignment of the lower extremity, affects knee and foot posture. Increased femoral anteversion and leg length difference may lead to increased *Q* angle, pronation of the foot, and hypermobility of the midfoot, and hypermobile joints may cause neuromuscular problems in maintaining balance [28]. The number of studies investigating the relationship between *Q* angle and navicular drop test and balance is limited. However, existing studies have associated the alignment with dynamic balance rather than static balance [29, 30]. This explains the low level of association with static balance measurement in our study. In studies examining the relationship between FPI-6 and postural sway, the fact that pronated foot posture leads to more sway has been explained by various mechanical, structural, and sensory mechanisms. Some of these mechanisms are that over pronation creates insufficient mechanical advantage for weight transfer, small changes in alignment make it difficult to use postural control strategies, and the amount of sensory input changes with the change in foot contact area [31]. Considering that these changes may be triggered by basic motor findings and postural deformities in patients with PD, the relationship between FPI-6 and our postural control findings gains meaning.

In the literature, a significant decrease in the ROM in the sagittal plane of the hip, knee, and ankle joints and lower pelvic tilt and rotation was found in PD compared to healthy older adults [32]. Our findings showed that flexion and abduction ROM of the hip joint, flexion ROM of the knee joint, and plantar flexion ROM of the ankle joint were associated with fall risk and balance performance in PD patients in accordance with the literature. While PD patients use less ankle dorsiflexion and knee flexion during stance and gait, the lower extremity movement torques produced also differ [33]. One of the responsible factors for the changes in the position and ROM of the lower extremity is rigidity, which is one of the motor findings of the disease. Rigidity causes a decrease in ROM and posture disorder and an increase in the speed and amplitude of postural sway. Postural reactions that should occur after perturbations are prevented due to rigidity; instead, loss of balance and falls occur in patients with more co-contraction of the muscles around the joint [34].

Approximately 75% of PD patients have a lack of balance control due to asymmetric motor deficits in both upper and lower extremities. It has been suggested that this is due to the fact that the motor findings of the disease first start unilaterally and then affect the contralateral side, but the involvement is more prominent on one side [35]. Although it is not known whether the difference in balance control is due to asymmetry in lower extremity biomechanics, our findings confirm the existence of this asymmetry.

Center of pressure (CoP), center of gravity (CoG), and postural sway are the most common indicators of postural balance. Laboratory-based assessments such as force platforms, motion capture cameras, and 3D gait analysis are effective methods for early detection of postural instability before falls. However, since these assessments require equipment and trained personnel, they are not cost-effective options, especially for clinics in rural areas [36]. Clinical biomechanical assessments may be useful in determining the need for further biomechanical assessment by detecting fundamental changes.

Compared to normative data reported in the literature for healthy individuals of similar age, participants with PD in our study showed approximately 20° less hip flexion, 23° less hip abduction, 49° less knee flexion, and 33° less ankle plantarflexion ROM [37, 38]. These findings suggest that the observed biomechanical differences—and their relationship with balance and fall risk—may be attributed more to Parkinson's disease itself rather than to age-related variability alone.

This study has several limitations that should be acknowledged. First, the observational and cross-sectional design precludes the ability to establish causal relationships between lower extremity biomechanical parameters and balance outcomes. To determine whether biomechanical impairments directly contribute to balance deficits—or whether targeted interventions can improve postural control—longitudinal or interventional studies are required. Second, although validated clinical tools such as the Biodex Balance System and Mini-BESTest were used to assess balance, the study did not include more advanced objective assessment techniques, such as three-dimensional gait analysis, motion capture systems, or electromyography (EMG). These tools could have provided a more detailed understanding of movement patterns, neuromuscular activation, and compensatory strategies in patients with PD. Third, the limited sample of the study may not fully reflect the clinical heterogeneity in terms of disease severity and functional level. The study was conducted at a single center and included a relatively homogeneous sample; participants were within a similar age range and exhibited mild to moderate disease severity (Hoehn and Yahr stages 1–3) and functional levels. This limits the generalizability of the findings to individuals with more advanced or atypical forms of Parkinson's disease. Future studies with larger and more diverse samples are needed to confirm and expand upon these findings. Finally, the absence of a healthy control group limits our ability to determine whether the observed biomechanical alterations are specific to Parkinson's disease (PD) or reflect normative variations in lower extremity alignment and joint mobility due to aging or other factors. Future studies need to include matched healthy controls to better distinguish PD-specific biomechanical changes from normative aging effects.

Conclusion

The findings of this study highlight the clinical relevance of evaluating lower extremity biomechanics in patients with PD. Specifically, parameters such as femoral anteversion angle, navicular drop, and Foot Posture Index, as well as hip, knee, and ankle joint range of motion, showed significant correlations with objective balance outcomes, including postural stability and fall risk. These findings suggest that asymmetries and limitations in lower extremity alignment and mobility may contribute to postural instability and increased fall risk in this population. Given the multifactorial nature of balance disorders in PD, the inclusion of biomechanical assessments of the lower limbs in clinical evaluations may offer valuable insights for the development of individualized therapeutic strategies.

Author contribution SD and RM: planning and design of the study; YE: recruitment and guidance of participants; SD and MSG: data collection; GY and AEY: contributed to data analysis. All authors contributed to the writing and revision of the manuscript. Additionally, all

authors have agreed to the final version to be published and agree to be accountable for all aspects of the work.

Data availability The datasets generated in the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval The study protocol was approved by the Ethics Committee of Clinical Research, Bezmiâlem Vakif University [E-54022451–050.04–189188]. Patients who voluntarily agreed to participate after being informed about the study were included. The study was conducted in accordance with the Declaration of Helsinki.

Consent to participate All participants provided written informed consent after being informed about the study, potential risks, and benefits.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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