Strategies for Maintaining Balance in Patients with Parkinson's Disease

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Abstract

Introduction. *The relevance of studying balance impairment in patients with Parkinson's disease (PD) lies in the need to prevent falls and injuries while enabling patients to maintain maximum independence and mobility. Promising advances in posture and gait screening using digital image processing require a thorough understanding of fundamental balance maintenance strategies.*

The study was aimed *at investigating balance maintenance strategies during PD "on" and "off" periods using classical and integral stabilometric parameters.*

Materials and methods. *The study included 27 PD patients with the median of 61 years. The mean total daily levodopa equivalent dose was 889.71 mg. All patients underwent clinical balance assessment using the Berg Balance Scale and stabilometric platform testing during "on" and "off" periods.*

Results. *Berg Balance Scale scores revealed mild balance impairments in PD patients, with greater severity during the "off" period ($p < 0.05$). Classical Romberg test parameters during the "on" period demonstrated deteriorated balance function and increased reliance on visual strategies for balance maintenance. Analysis of vector integral parameters during the "off" period showed a significant increase in angular velocity and coefficient of abrupt direction changes ($p < 0.05$). Stabilometry data indicate balance impairments in both PD "on" and "off" states, accompanied by different compensatory strategies.*

Conclusion. *Despite clinical assessments suggesting only mild balance impairments and low fall risk in PD patients, stabilometric parameters revealed more significant static balance disorders contributing to fall risk. Notably, the diagnostic value of classical stabilometric parameters decreases during the "off" period, while vector parameters characterizing balance maintenance strategies gain importance. We propose that these integral parameters can effectively assess balance quality and fundamental compensatory strategies in PD patients undergoing treatment. The findings are valuable for developing digitalized balance analysis technologies incorporating artificial intelligence.*

Keywords: *stabiliometry; Parkinson's disease; balance; postural control; risk of falls*

Ethics approval. All patients provided their voluntary written informed consent to participate in the study. The study protocol was approved by the Local Ethics Committee of the Russian Center of Neurology and Neurosciences (Protocol No. 3-6/22, April 20, 2022).

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Анализ стратегии поддержания равновесия у пациентов с болезнью Паркинсона

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Аннотация

Введение. *Актуальность проблемы нарушения равновесия у пациентов с болезнью Паркинсона (БП) обусловлена необходимостью предотвращения падений и травм, а также обеспечения возможности пациентам сохранить максимальную самостоятельность и мобильность. Перспективны разработки в области скрининга позы и походки с помощью цифрового анализа изображений, для которых важно понимание базовых стратегий поддержания равновесия.*

Цель *исследования – изучить стратегии поддержания равновесия в фазах «on» и «off» БП при помощи классических и интегральных показателей стабилометрии.*

Материалы и методы. *В исследование включены 27 пациентов с БП. Медиана возраста – 61 год. Среднее значение суточной эквивалентной дозы леводопы – 889,71 мг. Всем пациентам была проведена клиническая оценка равновесия по шкале баланса Берг и тестирование на стабилометрической платформе в фазах «on» и «off».*

Результаты. *По шкале баланса Берг у пациентов с БП отмечены лёгкие нарушения равновесия, более выраженные в фазе «off» ($p < 0,05$). Данные по классическим показателям теста Ромберга в фазе «on» показали ухудшение функции равновесия и преобладание роли зрения в стратегии её поддержания. При анализе векторных интегральных показателей в фазе «off» отмечено значимое увеличение угловой скорости и коэффициента резкого изменения направления движений ($p < 0,05$). Стабилометрические данные свидетельствуют о наличии нарушений равновесия в обеих фазах при БП, с разными компенсаторными стратегиями.*

Заключение. *Несмотря на наличие у пациентов с БП лёгких нарушений равновесия и низкого риска падения по данным клинической оценки, показатели стабилометрии на самом деле свидетельствуют о более серьёзных нарушениях статического равновесия, способствующих увеличению риска падения. Стоит отметить, что диагностическая значимость классических показателей стабилометрии в фазе «off» снижается, значимую роль приобретают векторные показатели, характеризующие стратегию поддержания равновесия. Мы считаем, что именно данная группа интегральных показателей может эффективно использоваться для оценки качества равновесия и базовых компенсаторных стратегий у пациентов с БП на фоне проводимого лечения. Эти результаты имеют ценность для дальнейших разработок цифровизированных технологий анализа равновесия с применением искусственного интеллекта.*

Ключевые слова: *стабилометрия; болезнь Паркинсона; равновесие; постуральный контроль; риск падения*

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Introduction

Scientific interest in studying balance and postural stability disturbances in Parkinson's disease (PD) is attributed to the fact that postural disorders are most strongly associated with an increased risk of falls, which can lead to serious consequences (fractures, traumatic brain injuries, etc.), including fatal outcomes [1–3]. Epidemiological data show that falls occur at least once in 50% of PD patients, with recurrent episodes observed in 35% of cases [4, 5].

The literature emphasizes the value of computerized stabilometry for studying various balance and vertical posture disorders in neurological diseases [6–8]. This method has long been recognized as an objective assessment of balance function and is actively empoyed in clinical practice [9]. Due to their widespread availability and potential for objective quantification of postural function data, stabilometric platforms are routinely employed to evaluate the effectiveness of rehabilitation methods and other therapeutic interventions.

Previous recommendations for stabilometric assessments favored simple, reliable parameters like path length, maximum deviations, and peak amplitude [10]. However, most software developers now propose using more complex integral indicators, as their analysis provides a more comprehensive evaluation of balance function and postural control strategies [11]. Integral indicators are mathematically derived parameters that assess various aspects of vertical posture regulation. These indicators lack universal standardization: different devices employ unique mathematical analyses of statokinesiograms. Nevertheless, most integral indicators fundamentally rely on relationships between center of mass displacement areas, path length and area, center of mass position and velocity, and similar vector parameters. These include the Romberg ratio, composite coefficient, displacement asymmetry coefficient, and similar metrics [12]. It is believed that the use of these indicators may reveal new mechanisms of vertical posture regulation in PD patients and enable comprehensive assessment of posturographic profiles. Previous studies have demonstrated the utility of integral indicators for evaluating balance function in PD, including pharmacotherapy monitoring [13–15].

Importantly, the symptoms of PD fluctuate throughout the day during specific therapy, which is associated with the onset (“on” state) and cessation (“off” state) of antiparkinsonian medication effects. The literature review shows that studies investigating postural function in PD typically assess patients exclusively in either the “on” or “off” state [16, 17], though no comparative studies have been conducted. We identified only one study with differentiated evaluation of balance function across both “on” and “off” states [6], which specifically analyzed the effects of apomorphine on postural stability.

Our hypothesis posits that PD patients may employ different compensatory strategies to maintain balance during “on” and “off” periods. Investigation of these state-dependent mechanisms in this patient population could facilitate the development of personalized digital screening programs and fall prevention strategies.

The study aimed to identify balance maintenance strategies in “on” and “off” states using classical and integrated stabilometric parameters.

Materials and methods

Stabilometry data were collected as part of a resarch approved by the Local Ethics Committee of the Scientific Center of Neurology (Protocol No. 3-6/22 dated April 20, 2022).

Inclusion criteria:
- clinical diagnosis of Parkinson’s disease (PD) established according to the criteria of the International Parkinson and Movement Disorder Society [18];
- Hoehn–Yahr stage II–III disease;
- age 40–80 years;
- provided consent for personal data processing and signed informed voluntary consent to participate in the study.

The study included 27 patients (14 women and 13 men) with a confirmed PD diagnosis, of whom 13 patients were at Hoehn–Yahr stage II and 14 at stage III. When assessing disease subtype, 4 patients were classified as having the akinetic/rigid PD, and 23 as the mixed PD. The median age was 61.56 [24; 75] years. The median levodopa equivalent daily dose was 889.71 [320; 2073.5] mg.

In accordance with the study objectives, patients underwent stabilometry testing during two daily periods: the “on” state (over 8 hours after levodopa intake) and the “off” state (1.0–1.5 hours after levodopa intake according to the treatment regimen). Additionally, 20 patients were examined twice daily during “on” and “off” periods at 1, 3, and 6 months. Data from repeated stabilometry studies were included in this analysis, resulting in a final total of 58 stabilograms analyzed for the “on” state and 58 for the «off” state.

All patients underwent baseline clinical balance assessment using the Berg Balance Scale [19] during “on” and “off” periods to identify postural stability differences between the both states.

Subsequently, patients underwent instrumental testing using the Stabilan 01-2 computerised stabilometry system (OKB RITM) during both “on” and “off” periods. This system is designed for computerised recording and mathematical processing of human center of pressure (CoP) position and displacement in a two-dimensional coordinate system during clinical diagnostic tests. The following clinical diagnostic tests were selected for patient examination and postural stability assessment:

1. The Romberg test consists of two components – with eyes open and closed – and is designed to assess static postural control while determining the role of vision in maintaining balance. This test serves as the primary and most frequently used assessment tool in various clinical diagnostic studies, essentially representing an instrumental version of the clinical Romberg test performed during routine neurological examinations [20]. The analysis of the findings involves comparing the metrics from eyes-open and eyes-closed trials. Normal values for this parameter range from 100 to 250. A value below 100 indicates that vision negatively affects balance function, with better stability observed eyes closed. A value exceeding 250 suggests that the patient predominantly relies on vision for balance maintenance, with significant deterioration when visual input is eliminated.

2. Limits of stability (LoS) testing evaluates the limits of stability during deliberate leans in one of four directions: forward, backward, right, and left. The normal ratio for forward/backward leans is 1.0–1.5, while the ratio for right/left leans should be 1.

In addition to specific assessments from the aforementioned tests, we analyzed stabilographic signals to evaluate three groups of integral stabilogram parameters:

1. Classical parameters – standardised stabilogram assessment methods applicable to all platform types, including CoP displacement, CoP sway velocity, statokinesiogram area (ellipse area), velocity index, curvature coefficients, CoP trajectory length, length-to-area ratio, and others.

2. Vector parameters characterizing the distribution of CoP velocity and acceleration vectors, including balance function quality, vectorogram area, abrupt direction change coefficient, linear and angular velocity indicators, vectorogram power, and others.

3. Spectral parameters reflecting the frequency spectrum of stabilographic signals in two planes: frontal and sagittal.

The stabilogram spectrum is divided into three main zones:

- High-frequency zone (2–6 Hz) – reflects CoP oscillations associated with physiological processes underlying balance maintenance; predominant amplitudes in this spectrum are often observed in various neurological disorders.
- Low-frequency zone (0.2–2.0 Hz) – indicates CoP oscillations associated with postural regulation through large muscle group contractions during specific balance challenges.
- Very low-frequency zone (0–0.2 Hz) – characterizes CoP oscillations related to fundamental postural adjustments observed during upright stance maintenance in healthy individuals [12].

Spectral parameters include peak amplitudes in statokinesiogram within frontal and sagittal planes, as well as power densities across stabilogram zones.

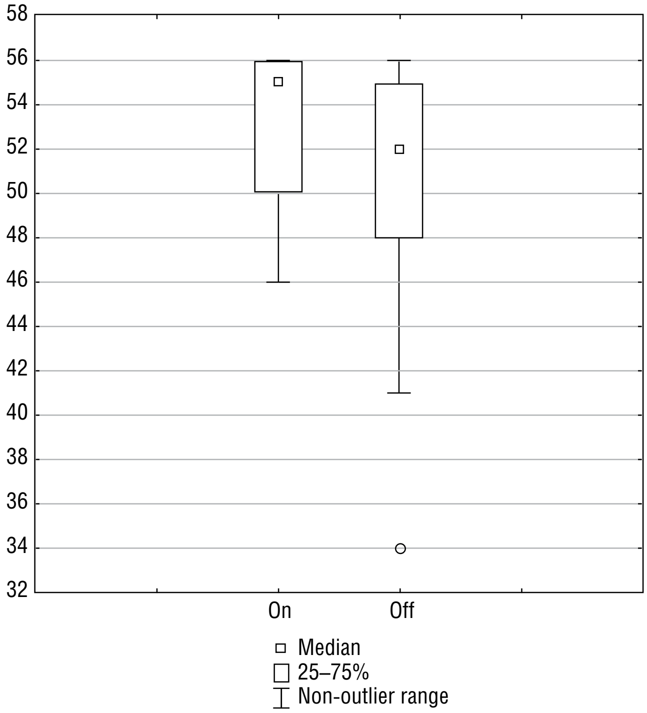

Fig. 1. Changes in the balance function on the Berg Balance Scale during “on” and “off” periods in PD.

Statistical analysis employed the Wilcoxon test (for paired comparisons) and Spearman’s correlation coefficient using Statistica v. 13.0 software (Statsoft). Data are presented as median values with interquartile ranges [Q_1; Q_3]. Results were considered statistically significant if $p < 0.05$.

Results

Analysis of clinical data using the Berg Balance Scale revealed that the median scores in PD patients during both “on” and “off” periods corresponded to mild balance impairment and low fall risk: 53.44 [50, 56] and 50.65 [48, 55], respectively. However, balance was significantly worse during the “off” period ($p = 0.001$; Fig. 1).

Following the stabilometric study, we analyzed the general data of the Romberg test (balance maintenance metrics with eyes open and closed) in PD patients during “on” and “off” periods (Table 1). A significant ($p = 0.005$) decrease in the Romberg ratio was observed in the “off” state, with its value normalizing compared to the “on” state. These changes may indicate a predominant reliance on visual input for balance strategy during the “on” periods, as balance function deteriorates sharply when visual input is removed. Analysis of group distribution based on Romberg ratio values in the “off” state revealed a significant shift toward proprioceptive reliance, with vision playing a markedly reduced role in balance maintenance during this period (Fig. 2).

A significant ($p = 0.001$) decrease was observed in the parameter characterizing the correlation between the CoP sagittal plane position relative to the intermalleolar line and CoP sway velocity with eyes closed. Normally, the mean value of this parameter is close to zero. This parameter primarily reflects the degree of CoP displacement during quiet standing posture maintenance (body position with straightened legs, upright trunk, neutral head alignment facing forward, and arms hanging freely at the sides) and, consequently, the intensity of compensatory response (increased gastrocnemius muscle tension) during ankle strategy implementation for balance control. Our data indicated that most patients exhibited CoP position values relative to the intermalleolar line significantly above or below zero during both “on” and “off” periods, reflecting forward or backward CoP displacement, respectively. However, during the “off” periods, patients showed parameter values approaching normal levels (Me = 0.94 [–1.76; 5.61]), suggesting reduced engagement of compensatory mechanisms for balance maintenance and potentially better postural stability during this period. The observed trend toward decreased length-to-area ratio with eyes open during the “on” state ($p = 0.06$) indicates reduced center of mass dispersion over the supporting area during this period. Existing literature associates low length-to-area ratio values with more energy-efficient balance strategies [12]. These changes combined with alterations in the CoP position coefficient relative to the intermalleolar line suggest that despite greater compensatory mechanism engagement, the “on” state demonstrates a more physiologically optimal balance strategy compared to the “off” state.

Subsequent balance function assessment involved analysis of statokinesiograms with eyes open (Table 2) and closed

Table 1. Changes in the general Romberg test parameters in PD patients Me [Q_1; Q_3]

Ratio	"On" state	"Off" state	Significance of differences between the states, *p*
Romberg ratio, %	218 [120; 351]	163 [99; 292]	0.005
CoP position relative to the intermalleolar line, mm^{-1}	2.59 [–0.56; 10.57]	0.91 [–1.76; 5.61]	0.001
Length-to-area ratio, mm^{-1}	0.78 [0.64; 1.12]	1.24 [0.77; 1.67]	0.06 (trend)

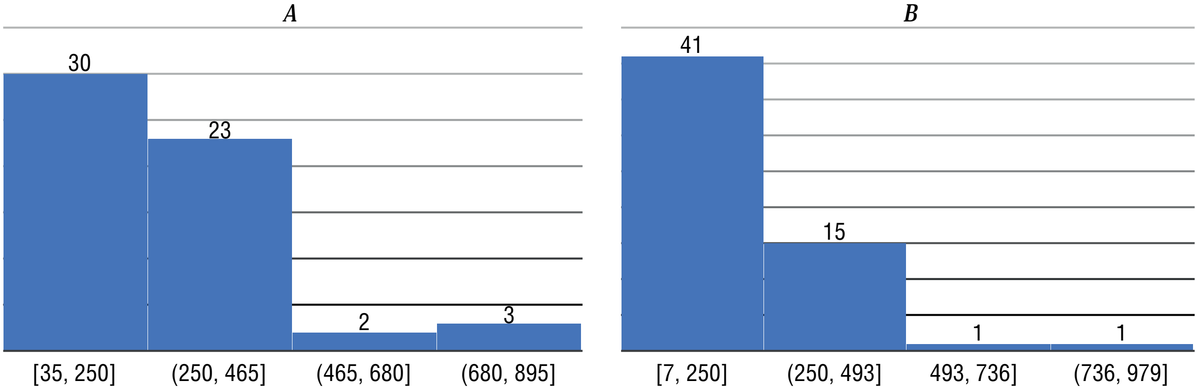

Fig. 2. Romberg ration distribution during "on" (*A*) and "off" (*B*) periods in PD.

(Table 3) using basic integrative parameters: classical, vector, and spectral parameters of postural control.

Statistical analysis yielded significant differences between the "on" and "off" states across all statokinesiogram parameters analyzed for both eyes-open and eyes-closed conditions.

Among classical parameters, special attention should be given to those describing the statokinesiogram ellipse area, i. e. the core portion of the stabilogram's total area (excluding random outliers and loops) which characterizes an individual's working support area. The primary parameter is the ellipse area. Its significant changes were observed in both "on" and "off" states. The ellipse area in the "on" state with open eyes increased by only 50 units (p = 0.049; Table 2), while with closed eyes it doubled (p = 0.001; Table 3). These changes likely result from significantly increased overall rigidity during the "off" period, restricting center of pressure (CoP) oscillations to a smaller plane, whereas transitioning to the "on" state reduces rigidity and expands CoP displacement dispersion. Literature suggests that increased ellipse area indicates impaired balance function, though its changes must be considered alongside other parameters [8, 12]. Additionally, eyes-closed statokinesiograms in the "on" state showed a significant decrease in the ellipse reduction coefficient (p = 0.049; Table 3). This coefficient reflects statokinesiogram "flattening", defined as the ratio of the ellipse's major axis length to its minor axis. Lower reduction coefficient values typically indicate more stable balance maintenance, as the stabilogram assumes an elongated shape. Analysis of statokinesiogram length revealed that "on" state changes primarily involve increased frontal plane displacement (Tables 2, 3). These findings suggest that "on" state transition expands lateral CoP oscillations while reducing anteroposterior sway. Thus, PD patients in the "off" state exhibit hypokinesia and marked muscle rigidity affecting both large intentional movements and automated motor functions – postural synergies. This conclusion is further supported by decreased CoP velocity index values (Tables 2, 3), indicating slower CoP displacement.

In further analysis, we examined the vector parameters of the statokinesiogram. This type of parameter characterizes the distribution of CoP velocity and acceleration vectors. The vector-based approach posits that with timely compensation of body deviations from the vertical, the CoP velocity should remain minimal. Conversely, impairments in the vertical posture regulation system would lead to delays and errors in correcting body deviations from the vertical, resulting in greater CoP displacements, higher velocities, and abrupt directional changes.

In this group of parameters, we observed changes in balance function quality (assessing how minimized the CoP velocity is) in both "on" and "off" states (Tables 2, 3). Normally, this parameter is 100%, where higher values indicate better balance maintenance. We noted a more pronounced decrease in the parameter with eyes closed in both states, with the "on" state showing significantly (p = 0.049) lower values than the "off" state (Table 3), suggesting more pronounced balance impairments in the "on" state. This is further supported by higher values in the "on" state for both mean linear velocity (p = 0.002) and linear velocity variation amplitude (p = 0.001) with eyes open and closed (Tables 2, 3).

However, despite the observed deterioration of balance function in the "on" state, we also obtained interesting data on vector parameters for the "off" state. Significant increases in the abrupt directional change coefficient were observed with both eyes closed and open (p = 0.001; Tables 2, 3), reflecting

Table 2. Changes in statokinesiogram parameters during Romberg test with eyes open in PD patients, Me [Q_1; Q_3]

Ratio	"On" state	"Off" state	Significance of differences between the states, *p*
Classical parameters			
Mean CoP sway velocity	8.64 [6.92; 13.11]	8.43 [6.56; 10.24]	0.049
Velocity of changes in the statokinesiogram area	13.55 [7.60; 14.30]	9.50 [7.60; 14.30]	0.026
Ellipse area	148.35 [89.50; 273.10]	102.80 [77.40; 156.60]	0.049
Velocity index	5.49 [4.41; 8.24]	5.34 [4.12; 6.52]	0.05
Frontal CoP trajectory length	96.50 [73.50; 155.80]	90.20 [63.10; 109.20]	0.012
Vector parameters			
Balance function quality	84.61 [66.54; 89.85]	85.29 [79.45; 90.94]	0.013
Abrupt direction change coefficient	9.08 [4.62; 13.45]	14.26 [9.44; 18.88]	0.001
Mean linear velocity	8.65 [6.92; 13.11]	8.44 [6.55; 10.25]	0.049
Linear velocity variation amplitude	5.12 [4.06; 8.87]	4.60 [3.77; 7.10]	0.003
Mean angular velocity	17.95 [13.10; 23.90]	23.65 [18.50; 28.10]	0.001
Angular velocity variation amplitude	19.80 [16.40; 24.00]	22.10 [18.60; 27.50]	0.003
Spectrum parameters			
2nd peak amplitude, sagittal plane	2.40 [1.51; 3.03]	1.65 [1.20; 2.21]	0.005

the proportion of abrupt velocity vector turns (> 45°) relative to the total vectors. Additionally, significant increases were found in angular velocity variation amplitude ($p = 0.001$) and accumulated displacement angle ($p = 0.026$), corroborating the findings for the abrupt directional change coefficient. The "off" state changes suggest that despite an apparent state of greater stability, stabilometric data reveal persistent alterations in balance maintenance strategies. These conclusions are reinforced by increased statokinesiogram power in the "off" state, indicating larger-amplitude velocity vector oscillations and a coarser (abrupt-movement) balance strategy compared to the "on" state.

Thus, analysis of vector parameters reveals that despite existing balance impairments, patients in the "on" state demonstrate a more physiological and smoother balance maintenance strategy. This is evidenced by altered indicators reflecting the activity of muscles responsible for physiological ankle strategy implementation (triceps surae muscle), along with lower values of vector parameters indicating abrupt changes in CoP direction compared to the "off" state. In the "off" state, despite less pronounced deviations in statokinesiogram area parameters, sharper vector changes with higher velocities are observed, suggesting reduced compensatory potential for maintaining upright posture in the standard stance. These findings are supported by more pronounced balance function impairments on the Berg Balance Scale, which shows significantly worse scores in the "off" state. This scale includes multiple dynamic tests assessing postural instability during task performance. The observed statokinesiogram changes in the "off" state indicate that patients experience greatest difficulties during body position transitions, as physiological smooth balance compensation becomes compromised.

We performed an analysis of spectral parameters as an additional tool to assess changes in stabilographic signals across two planes (frontal and sagittal). The principal differences between patients in "on" and "off" state were observed in the amplitudes of statokinesiogram spectral peaks, though in most cases, these remained within the high-frequency oscillation range associated with physiological processes (Tables 2, 3). However, with eyes closed, patients in the "off" state exhibited amplitude shifts in the 1st, 2nd, and 3rd peaks, which represent the amplitude of the three most prominent CoP oscillations on the stabilogram spectrum below the high-frequency range – indicating a predominance of CoP oscillations required for postural control and balance maintenance.

Analysis of the LoS test revealed significantly fewer differences between "on" and "off" state in PD. The evaluation of lateral displacements (right, left, forward, backward) and classical stabilometric parameters showed no statistically significant changes in balance function during either period. Notably, the main differences in the LoS test were observed in vector parameters and one spectral parameter of the statokinesiogram (Table 4). These statokinesiogram parameters help characterize the velocity of CoP movements in terms of compensatory response.

During the LoS testing, patients with PD in the "off" state showed a significant increase in the coefficient of abrupt directional change, mean angular velocity, and amplitude of angular velocity variation. Additionally, a notable difference was observed in the linear-to-angular velocity ratio, which was significantly lower in the "on" state compared to the "off" one, indicating that the linear CoP displacement velocity during the "on" period exceeds the angular velocity. This parameter, along with vector indicators, confirms that the

Table 3. Changes in statokinesiogram parameters during Romberg test with eyes closed in PD patients, Me [Q_1; Q_3]

Ratio	"On" state	"Off" state	Significance of differences between the states, *p*
Classical parameters			
Mean CoP sway velocity	13.66 [10.90; 27.97]	12.12 [8.93; 18.13]	0.002
Velocity of changes in the statokinesiogram area	26.10 [16.70; 62.10]	18.20 [11.20; 35.20]	0.001
Ellipse area	313.9 [194.0; 474.90]	160.90 [103.0; 306.10]	0.001
Ellipse reduction coefficient	1.64 [1.29; 2.17]	1.79 [1.45; 2.44]	0.049
Velocity index	8.53 [6.82; 17.56]	7.05 [5.58; 11.12]	0.002
Frontal trajectory length	137.05 [88.90; 262.10]	120.50 [79.90; 168.50]	0.001
Sagittal trajectory length	192.9 [134.50; 273.80]	199.80 [156.90; 403.40]	0.049
Vector parameters			
Balance function quality	64.89 [44.97; 76.15]	71.72 [48.69; 83.74]	0.049
Abrupt direction change coefficient	6.93 [5.12; 9.44]	11.65 [7.23; 15.65]	0.001
Mean linear velocity	13.66 [10.88; 27.97]	12.12 [8.93; 18.14]	0.002
Linear velocity variation amplitude	10.19 [6.89; 17.56]	7.64 [6.04; 11.17]	0.001
Mean angular velocity	15.30 [12.90; 19.30]	20.65 [16.20; 25.40]	0.001
Angular velocity variation amplitude	17.95 [16.30; 21.90]	21.85 [19.0; 24.80]	0.001
Accumulated displacement angle	0.22 [-2.40; 4.04]	-0.60 [-4.29; 1.51]	0.026
Linear-to-angular velocity ratio	0.84 [0.58; 1.45]	0.61 [0.45; 0.90]	0.001
Spectrum parameters			
1st peak amplitude, frontal plane	4.67 [3.57; 6.0]	2.99 [2.13; 4.0]	0.001
2nd peak amplitude, frontal plane	3.0 [1.95; 3.95]	1.91 [1.36; 2.55]	0.001
3rd peak amplitude, frontal plane	1.97 [1.38; 2.82]	1.37 [0.91; 1.82]	0.001
3rd zone power	12 [10.0; 15.0]	14 [12.0; 17.0]	0.002
1st peak amplitude, sagittal plane	7.1 [5.32; 8.78]	5.39 [3.34; 7.41]	0.001
2nd peak amplitude, sagittal plane	3.75 [3.01; 5.28]	3.09 [2.42; 3.87]	0.002
3rd peak amplitude, sagittal plane	2.63 [1.93; 3.59]	2.11 [1.54; 2.66]	0.026

balance maintenance strategy during the "on" period is more physiological. The changes observed during testing suggest that, despite unaltered lateral displacement amplitude, the balance maintenance strategy becomes sharper (with more abrupt movements) during both the static-dynamic displacement test and the static Romberg test, where similar "off"-state responses were noted. Despite statistically significant changes in the amplitude of the first sagittal-plane peak on spectral analysis, these changes occurred within the high-frequency spectrum range, reflecting normal compensatory responses during the static-dynamic displacement test in both "on" and "off" states.

Discussion

Studies have shown that although levodopa medications effectively reduce muscle rigidity and stiffness, they may lack an impact on postural function [21]. Therefore, we should identify key parameters of postural instability both during and without antiparkinsonian therapy, which could facilitate the development of screening tools and effective fall risk prevention strategies.

Our study identified key parameters characterizing postural impairments in PD patients and their differences between "on" and "off" state associated with medication effects. Specifically, PD patients during the "on" period demonstrated an increased Romberg ratio, reflecting vision's role in maintaining balance function, i.e., static balance deteriorated when visual control was eliminated. These findings align with research confirming the predominant role of vision in balance maintenance for PD patients [22, 23]. However, visual component significantly diminishes in the "off" state, suggesting a shift in balance control mechanisms toward reliance on pro-

Table 4. Changes in statokinesiogram parameters during LoS test with eyes closed in PD patients, Me [Q_1; Q_3]

Ratio	"On" state	"Off" state	Significance of differences between the state, *p*
Vector parameters			
Abrupt direction change coefficient	6.73 [5.10; 9.26]	8,39 [6,26; 12,20]	0.001
Mean angular velocity	15.30 [12.50; 17.90]	17.10 [14.10; 21.80]	0.001
Angular velocity variation amplitude	18.20 [17.10; 19.70]	19.20 [17.10; 21.40]	0.004
Linear-to-angular velocity ratio	1.84 [1.41; 2.55]	1.58 [1.21; 1.98]	0.003
Spectrum parameters			
1st peak amplitude, sagittal plane	38.55 [31.69; 47.19]	37.65 [28.76; 44.12]	0.049

prioception. Some studies also report similar balance maintenance strategies in PD patients, though researchers typically attribute these changes to disease stage without specifying the assessment period [24]. Thus, balance function impairment persists in both periods, consistent with select study data [25], but compensation strategies differ.

Among classical parameters, the ellipse area (statokinesiogram area) stands out: its value with eyes closed was twice as high as with eyes open during the "off" period, and 1.5 times higher in the "on" one. These changes confirm the aforementioned Romberg ratio alterations and indicate worse balance maintenance in PD patients when visual input is removed. Similar changes have been identified by other researchers [26], confirming impaired balance function in stage 2–3 PD patients with eyes closed, though these studies did not specify the period during stabilometric testing. Our data align with previous studies comparing PD subtypes, which demonstrate comparable statokinesiogram area changes and CoP velocity alterations in patients with akinetic-rigid PD [27].

Comparison between different periods revealed that the value during the "off" period was twice as low as during the "on" period, both with eyes open and closed (accounting for changes in both conditions). These observed changes are most likely associated with increased overall rigidity in patients during the "off" period due to the wearing-off of levodopa, resulting in reduced body displacement during vertical posture maintenance. As previously demonstrated, patients receiving antiparkinsonian therapy show some increase in statokinesigram area with eyes closed compared to untreated patients [28], which generally aligns with our findings. However, the cited study reported less pronounced balance impairments, potentially due to the inclusion of patients with milder PD severity. Thus, this integral parameter (statokinesigram area) may serve as a significant marker of static balance function impairment in PD patients even at early disease stages, particularly during the "on" period. In turn, using this parameter as the primary marker during stabilometric assessment in the "off" state could lead to misinterpretation, especially in mild balance impairments, since its value is statistically significantly lower than that during the "on" period, as demonstrated in our study. The observed smaller statokinesigram area in the "off" state, likely attributable to greater rigidity limiting body sway, is further supported by our findings of reduced overall CoP velocity during both eye-open and eye-closed conditions in this period.

Although our data on classical statokinesiogram parameters reflecting static balance impairments were worse during the "on" period, further analysis of integral parameters revealed mechanisms underlying balance disorders and influencing fall risk elevation in during "off" period. Analysis of vector parameters demonstrated an increase in the coefficient of abrupt direction changes, angular velocity variation amplitude, and accumulated displacement angle during the "off" period. These changes characterize compensatory strategies employed by patients during the "off" period to maintain static balance as fall-risk-prone. During this periods, patients maintain balance predominantly through abrupt changes in CoP sway direction with high angular velocity, which may adversely affect dynamic balance (during body position changes) and lead to falls when movement direction changes or body repositioning is required. Additionally, vector parameters reflecting abrupt CoP sway direction changes may serve as reliable markers of balance impairments in the "off" state, unlike classical stabilometric parameters that show closer alignment with reference values (and sometimes even normal) during "off" periods compared to "on" ones. We consider that this group of integral parameters could be effectively used to assess balance quality and fundamental compensatory strategies in PD patients undergoing treatment. Our literature review revealed no previous analyses of such parameters in PD.

The data we obtained on identified compensatory responses characterizing balance disorders in the "off" state are further supported by an additional analysis of the spectral component of the statokinesiogram. A shift in spectral amplitudes toward low-frequency oscillations was detected, which are utilized by the body as compensatory responses to maintain upright stability. The observed predominance of high-frequency oscillations in the "on" state, characterizing physiological processes in the body, has been linked in the literature to an increased risk of falls in PD patients [13].

On one hand, our findings demonstrate that during the "on" period, patients exhibit more pronounced balance function impairment, particularly with eyes closed, which may be associated with increased fall risk due to reduced overall rigidity and consequent deterioration of postural functions. On the other hand, despite the seemingly greater stability of patients in the "off" state, pronounced compensatory responses – manifested as more abrupt CoP sways to maintain stability – also contribute to elevated fall risk in PD patients. These very responses may explain the increased frequency of falls in PD patients during morning and nighttime hours when, due to lack of medication effects, patients cannot effectively utilize physiological strategies for maintaining balance function.

Conclusion

Postural instability is a significant PD symptom that can subsequently lead to increased falls and associated severe, often disabling consequences. The findings revealed that despite clinically mild balance impairments according to the Berg Balance Scale, stabilometric assessment demonstrated pronounced static balance disturbances in patients. Analysis of stabilogram integral parameters during "on" and "off" periods allowed us to identify key mechanisms underlying balance maintenance strategies in the upright posture during these periods, as well as to determine core groups of stabilometric parameters reflecting balance impairment: increased statokinesiogram area and velocity indices of CoP displacement, along with their dependence on visual control.

Thus, patients with PD exhibit marked balance impairments while maintaining an upright posture during both "on" and "off" periods; however, the compensatory strategies employed by patients differ between these periods. This underscores the necessity of performing stabilometric assessments in both states when conducting clinical or rehabilitation studies addressing postural impairment correction in this patient population.

The use of integrated stabilometric parameters serves to assess balance function and identify balance maintenance strategies in PD patients. They are also valuable for developing digitalized balance analysis technologies employing artificial intelligence, which could automate and streamline population screening while facilitating implementation of fall prevention measures.

Study limitations This study included patients with drug-induced dyskinesias: severe dyskinesias were observed in 8% of cases, moderate dyskinesias in 15%. During mathematical processing of CoP sway data, software algorithms were used to eliminate extreme outliers occurring during these movements. Calculation of integral parameters excluded abrupt CoP sways.

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