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Supervised aerobic-strength exercise reduces postural sway and improves dual-task gait in Parkinson's disease

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Parkinson's disease (PD) impairs balance and gait, increases fall risk, and reduces quality of life. While levodopa remains the primary treatment, it has limited effects on postural instability. Exercise training offers complementary benefits. This study examined the effects of supervised aerobic-strength exercise on postural stability and gait in PD patients, focusing on differences between ON and OFF medication states and relationships between static balance and dynamic balance during normal and dual-task walking. Fifteen PD patients completed a 4-month exercise training, with pre- and post-intervention assessments in both medication states using trunk accelerometry for static balance assessment during stance with eyes open and closed on firm and foam surfaces; and a markerless camera system for dynamic balance assessment during walking. The MDS-Unified Parkinson's Disease Rating Scale (MDS-UPDRS) and Berg Balance Scale (BBS) were utilized. Post-intervention, motor MDS-UPDRS scores improved significantly in both ON ($p = 0.013$) and OFF ($p < 0.001$) states. BBS scores increased ($p = 0.005$), and several postural parameters decreased in the OFF state in multiple conditions. During dual-task walking, stance time decreased in both ON ($p = 0.048$) and OFF ($p = 0.026$) states, while walking speed increased ON medication ($p = 0.018$). Trunk sway reduction correlated positively with stance time during dual-task walking. However, correlations between postural and gait changes without dual-task were either absent or inverse. These findings suggest that aerobic-strength exercise enhances postural stability and dual-task gait performance, particularly OFF medication. The distinct correlations between changes in postural and gait parameters indicate that specific tasks uniquely affect motor function outcomes, highlighting the need to fine-tune examination strategies in movement disorder research.

Keywords Parkinson's disease, Medication, Balance, Gait, Exercise training

Parkinson's disease (PD) is currently the second most common neurodegenerative disorder after Alzheimer's disease[1]. There is an increasing incidence of PD, mainly due to the aging of the population and sedentary lifestyle[2,3] with a sharp increase around the age of 65 years[4]. PD is characterized by four cardinal motor symptoms: bradykinesia, rigidity, resting tremor, and postural instability. These symptoms mostly affect balance during standing (sway), anticipatory postural adjustments (APAs), reactive postural responses, and gait[5,6]. Postural instability in PD is associated with reduced magnitude of postural sway[7], increased postural sway jerkiness[8], reduced APAs[9], and reduced limits of stability[10]. Scaling of postural responses and sensorimotor integration are also impaired[11], increasing the risk of falls in PD patients. Previous studies reported increased postural

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responses with more severe destabilization in PD patients after sudden changes in sensory inputs , suggesting impairments in sensory reweighting[12–14]. Balance problems magnify with disease progression and result in a greater inability to perform daily activities and, thus, loss of independence[15,16]. Consequently, PD patients have a reduced quality of life, especially in physical functions and mental health domains[17].

Dynamic balance involves controlling the body's center of mass (CoM) relative to, but not necessarily directly over, a moving base of support. Walking becomes less automatic in PD so it requires more attention, particularly for challenging tasks such as turning or dual-tasking[18]. Gait as a complex balancing task demands axial control of lateral and forward stability and appropriate, well-timed foot placement to control stability and the constantly shifting CoM[6]. Walking puts CoM beyond the anterior limits of stability, which is arrested by a step that is placed in front of CoM to keep a person from falling[6]. In patients with PD, multiple aspects of gait are specific, such as pace, rhythmicity, and asymmetry[19]. As changes in gait and cognition are interconnected[20,21], dual-task constructs allow us to study the relations between the two. Previous research shows that while performing dual tasks, patients with mild-moderate PD have a generalized worsening of spatiotemporal gait parameters when an attention, memory, information processing, visuospatial, or verbal memory task is performed concurrently[21].

Levodopa treatment is still the most effective treatment for PD; however, as PD progresses, both motor and non-motor symptoms emerge that are less responsive to dopaminergic medication[22]. However, even the levodopa treatment poses challenges such as motor fluctuations, i.e., early morning akinesia, freezing, wearing off, and dyskinesia[23]. Postural instability is also shown to be poorly responsive to levodopa medication[24,25]; certain balance dysfunction even worsens under pharmacological treatment[6]. Mounting evidence strongly supports positive effects of regular aerobic and/or strength exercise on the clinical state and quality of life, providing a wide spectrum of motor and non-motor health benefits in patients with PD[26–30]. Aerobic and/or strength training interventions have been associated with improved general functional performance during a quiet stance, as evidenced by assessments such as the MDS-UPDRS and BBS[30,31]. Additionally, improvements in balance and functional mobility have been demonstrated through increased gait speed[29–34], reduced center of pressure (CoP) sway path[35], and decreased CoP velocity[34].

In recent years, technology has significantly advanced our ability to measure and analyze human balance and motion, particularly in the context of medical monitoring[36]. Body-worn inertial sensors with inbuilt accelerometers capture the acceleration of body segments, allowing us to objectively assess postural control and distinguish specific manifestations of balance dysfunction in patients with PD[5,37–44]. Markerless camera systems bring a novel approach that allows capturing movements without the need for physical markers on the body[45]. Thanks to the pose estimation algorithms based on artificial intelligence together with the technology to retrieve depth, spatiotemporal gait parameters can be captured faster[45,46], providing reproducible and clinically relevant data with greater ecological validity in PD patients[47–50].

Previous studies have often focused solely on either posture or gait parameters or have assessed PD patients only in either the ON or OFF medication state, potentially overlooking the impact of dopaminergic medication. This study aims to fill these gaps by evaluating the impact of aerobic-strength exercise intervention on postural control and gait in PD patients, focusing on the differences between medication states (ON and OFF) and the interrelations between walking and static postural balance. By leveraging advanced technologies such as accelerometers and the markerless system for motion analysis, this research seeks to understand how exercise affects balance in relation to gait, thereby enhancing the quality of life and functional independence of PD patients. We hypothesize that aerobic-strength exercise intervention will have differential effects on postural and gait parameters across medication states, with specific improvements underpinning the enhanced motor function and stability in PD patients.

Methods

Participants

Twenty-six participants underwent the 4-month supervised aerobic-strength exercise intervention. Four participants were excluded due to missing (unusable) data from gait measurements, three participants were excluded due to missing (unusable) data from postural measurements, three participants were excluded due to the lower than required 75% training attendance (due to health issues or non-compliance); and one participant was excluded due to temporarily compromised mobility during the post-intervention measurement window (musculoskeletal injury). The data from 15 individuals with idiopathic PD were analyzed. The clinical study flow chart is shown in the Supplementary Fig. 1. Participant characteristics including anthropometric and clinical measures are listed in the result section with their change after the intervention (Table 1). Diagnosis of idiopathic PD was determined by a movement disorder specialist based on criteria by Postuma et al. 2015[51]. Included in the study were patients in the early to middle stages of Parkinson's disease (Hoehn and Yahr stages 1–2) who were aged 55–80 years, able to walk independently for long distances without assistive devices, and had no prior rehabilitation experience. Patients with chronic systemic cardiovascular, hepatic, renal diseases, or cancer were excluded, as were those who were noncompliant. All PD patients received standard care from a neurologist during outpatient visits and were on appropriate PD medication (L-DOPA/carbidopa, dopamine agonists, MAO inhibitors, COMT inhibitors), the doses and types of which did not change during the intervention. The severity of PD was rated by the trained clinical examiner on the Motor Section (III) of the MDS-Unified Parkinson's Disease Rating Scale (MDS-UPDRS) and the Hoehn and Yahr Scale was assessed immediately before the first experimental session. The protocol was approved by the Ethics Committee of the University Hospital Bratislava and the Ethics Committee of Bratislava Region, and conformed to the ethical guidelines of the Helsinki Declaration of 1964 (2013 revision). All individuals signed a written informed consent prior to study entry, including disclosure of the data obtained. The study was registered on ClinicalTrials.gov under the registration number NCT03330470, with the first date of registration on 30/10/2017.

Group characteristics	
n	15
Age (years)	65.53 (6.82)
Male (number)	11
Disease duration (years)	4.0 (3.34)
Hoehn & Yahr scale	2.0 (0.0)
LEDD (mg/day)	641.93 (469.11)

	PRE - intervention	POST - intervention	*P*-value
Anthropometric measures			
Body height (cm)	173.20 (9.17)	173.35 (9.11)	0.120
Body weight (kg)	84.05 (17.71)	82.67 (17.85)	0.060†
Waist circumference (cm)	102.11 (15.32)	97.61 (15.73)	0.326
BMI ($kg.m^{-2}$)	28.14 (6.23)	27.64 (6.28)	**0.035**
Body fat (%)	28.35 (11.70)	25.59 (10.21)	**0.035**
Body muscle (%)	31.35 (5.77)	32.27 (5.43)	0.055†
Visceral fat content (AU)	11.73 (5.79)	11.13 (5.42)	**0.021**
Clinical measures			
MDS-UPDRS-III (score)			
OFF	31.67 (9.36)	26.27 (6.68)	< **0.001**
ON	21.86 (8.38)	18.86 (7.09)	**0.013**
BBS (score)			
OFF	52.71 (2.79)	54.50 (2.10)	**0.005**
ON	53.86 (2.54)	54.43 (1.45)	0.755
TUG (s)			
OFF	9.29 (2.35)	8.93 (1.60)	0.561
ON	8.79 (1.95)	8.59 (1.26)	1.0
10MWT at preferred speed (s)			
OFF	8.46 (1.03)	8.66 (1.51)	0.890
ON	8.07 (1.18)	8.22 (1.05)	0.542
10MWT at maximal speed (s)			
OFF	5.20 (1.09)	5.01 (0.81)	0.389
ON	4.95 (1.11)	4.81 (0.77)	0.556

Table 1. Characteristics of the study population and the effects of a 4-month aerobic-strength exercise intervention on anthropometric and clinical measures in patients with Parkinson's disease. Data are shown as group mean (± SD). P-values indicate significance level showing differences between PRE and POST measurements, significant changes ($p < 0.05$) are in bold and trends ($p \geq 0.05$ and $p < 0.10$) are marked with †. LEDD - L-dopa Equivalent Daily Dose, BMI – Body Mass Index, MDS-UPDRS – MDS-Unified Parkinson's Disease Rating Scale, BBS - Berg Balance Scale, TUG - Timed Up and Go test, 10MWT – 10 m Walk Test, ON – ON medication state, OFF – OFF medication state.

Measurement set-up and procedure

Supervised aerobic-strength exercise intervention

A supervised 4-month intervention combining both strength and aerobic-coordination exercises was designed based on the previous experiences from a pilot clinical study[29], and performed at the Centre for Physical Activity Research of the Biomedical Research Center of Slovak Academy of Sciences. The training program was tailored to each participant's physical fitness and muscle strength as assessed prior to the intervention. It was conducted three times a week, always beginning with a 10-minute warm-up and ending with cool-down and stretching exercises. Strength training was performed twice weekly on non-consecutive days, with each session lasting 60 min. The exercises targeted the major muscle groups of the upper and lower extremities and were conducted at 50–60% of one-repetition maximum (1RM). Exercises were performed with weight machines, resistance bands, light/moderate handheld weights and body weight. Maximal voluntary contraction force of the major muscle groups was assessed by dynamometry. The weekly aerobic-coordination training session lasted 60 min and included exercises performed at 60–70% of the maximum heart rate (HRmax). Maximal aerobic capacity (VO_2max), a parameter of cardiopulmonary fitness, was assessed at baseline using the Rockport Walking Test. A progressive increase in training intensity was based on performance improvements. Participants were instructed to maintain their dietary habits. Attendance of > 75% of training sessions and no training absence within the last two weeks of the training period were prerequisites for the succesfull completion of the exercise intervention. The capacity to perform exercise intervention was assessed by a cardiologist and neurologist. Recruitment of PD patients into the control group (no exercise intervention) was attempted but abandoned for both practical and

ethical reasons. Although patients entering the control arm were offered the identical exercise intervention after completing the study protocol as controls, interest in entering the control group was negligible.

Measurement protocol

Anthropometric parameters (body height, body weight, BMI and waist circumference) as well as body composition parameters (body fat, body muscle, and visceral fat content) were measured before the start of the aerobic-strength exercise intervention (PRE) and shortly after the end of the intervention (POST). Body composition was assessed by quadrupedal bioelectric impedance (Omron BF-511, Japan). Clinical scales and tests (Berg Balance Scale, Timed Up and Go test, 10 m Walk Test) reflecting overall posture and gait as well as specific posturographic and gait measurements were also performed PRE and POST intervention. All measurements were conducted under two distinct conditions: the "ON" medication state, one hour after morning antiparkinsonian medication intake, and the "OFF" medication state, scheduled on a separate day within the same week. For the "OFF" medication state assessments, patients were asked to refrain from taking their antiparkinsonian medication for at least 12 h before the measurements. Posture and gait parameters were obtained on the same day, with static balance being measured first. The measurements were always carried out at the same time of the day.

Posturography

During the postural stability assessment, participants were instructed to maintain an upright standing position on a custom-made force plate (45 × 45 × 6.5 cm; see details in Hirjaková et al.[52]), with the head in a straight-ahead position, arms along the body and feet hip-width apart. During conditions with eyes open, patients focused their gaze on a stationary eye-level visual target (a black spot with a diameter of 1.5 cm) situated in a white scene at a 1.5 m distance in front of them. The initial stance position was consistent from trial to trial by tracing foot outlines on the force plate.

Steady postural balance was measured using trunk accelerometry by two inertial sensors (MTw, Xsens Technologies, B.V., The Netherlands) with inbuilt 3D accelerometers (± 1.7 g range) attached to the anterior trunk at the level of the sternum (ST) and the posterior trunk at the level of the fifth lumbar vertebra (L5). Acceleration signals were collected with a 100-Hz sampling frequency and filtered with a 3.5 Hz cut-off, zero-phase, low-pass Butterworth filter[40]. The sensing axes were oriented in the anatomical anterior-posterior (AP), medial-lateral (ML), and vertical directions.

The postural assessment consisted of four static conditions challenging different demands on afferent sensorimotor control. Testing of static postural stability included: stance on a firm surface with eyes open (EO); stance on a firm surface with eyes closed (EC); stance on a foam surface (50 × 41 × 6 cm, Airex Balance Pad, Switzerland) with eyes open (FEO) and stance on a foam surface with eyes closed (FEC). The duration of each trial was 60 s with a fixed order of experimental conditions.

For each trial, four variables were calculated from the resultant 2D acceleration measured at both L5 and ST levels: (1) sway area (SA), computed as the area enclosed by the acceleration path per unit of time (m^2/s^5); (2) sway path (SP), as the total length of acceleration path (m/s^2); (3) mean frequency (MF), as the number of loops, per second, that have to be run by the acceleration path to cover a total acceleration trajectory (Hz); (4) sway jerkiness (JERK), as the time derivative of acceleration (m^2/s^5). This set of parameters was chosen to adequately characterize different aspects of postural sway in PD patients, according to Mancini et al.[37,38]. The center of pressure displacement was also calculated from the ground reaction forces recorded by the force plate; however, the results are not reported here.

Gait analysis

The walking was assessed using the markerless Microsoft Azure Kinect DK (Developer Kit). The Azure Kinect DK was placed 7.5 m in front of the start point for walking and 0.8 m above the floor (Fig. 1), turned up at around 6°. The sample rate of the Azure Kinect depth camera was 30 Hz with a resolution of 320 × 288 pixels and a field of view of 75° x 65°; the RGB camera recorded at the same frequency. The Azure Kinect Body Tracking SDK version 1.1.0 was used to record the position change dynamics of 32 joints, including the ankles, knees, and hips. Marker trajectories were filtered using a Woltring generalized cross-validatory interpolating spline (5th order). The gait assessment began with participants initiating their walk 7.5 m away from the camera, moving directly towards it. Upon reaching a point 0.5 m in front of the camera, they executed a U-turn and proceeded to walk back (Fig. 1). This sequence was repeated three times for one trial. Two conditions were measured: normal walking with participants walking at their preferred speed; and dual-task walking (DT) with participants performing a cognitive task during walking. Participants first performed normal walking, then the walking was performed with a dual-task, then repeated all tasks for a second time. The DT walking consisted of an untimed serial subtraction task added to the normal walking. The participant was required to subtract three from the starting number 107 or 108, verbalize the result, and continue the process until no further subtractions could be made while walking. The correctness of counting was not taken into account.

Based on our preliminary study comparing the GAITRite® and our own developed algorithm in healthy young adults, we extracted several metrics. The primary gait metrics included speed (m/s), step length (m), and duration of the stance phase - stance time (s). Gait speed was calculated as the distance covered divided by the time taken (m/s). Step length was measured as the peak distance between left and right ankle points, and its variability was assessed through the step length's covariance. Stance time was calculated as the time duration from where the ankle joint speed in the z-axis was lower than 10% of its peak (stopped moving) until it reached 10% of its maximal speed in the next gait cycle. Stance time variability was evaluated by the covariance of the stance time. These measurements were averaged across both the left and right legs. Data collected from two trials were averaged. In instances where an error occurred in one of the trials, only the valid measurement was used.

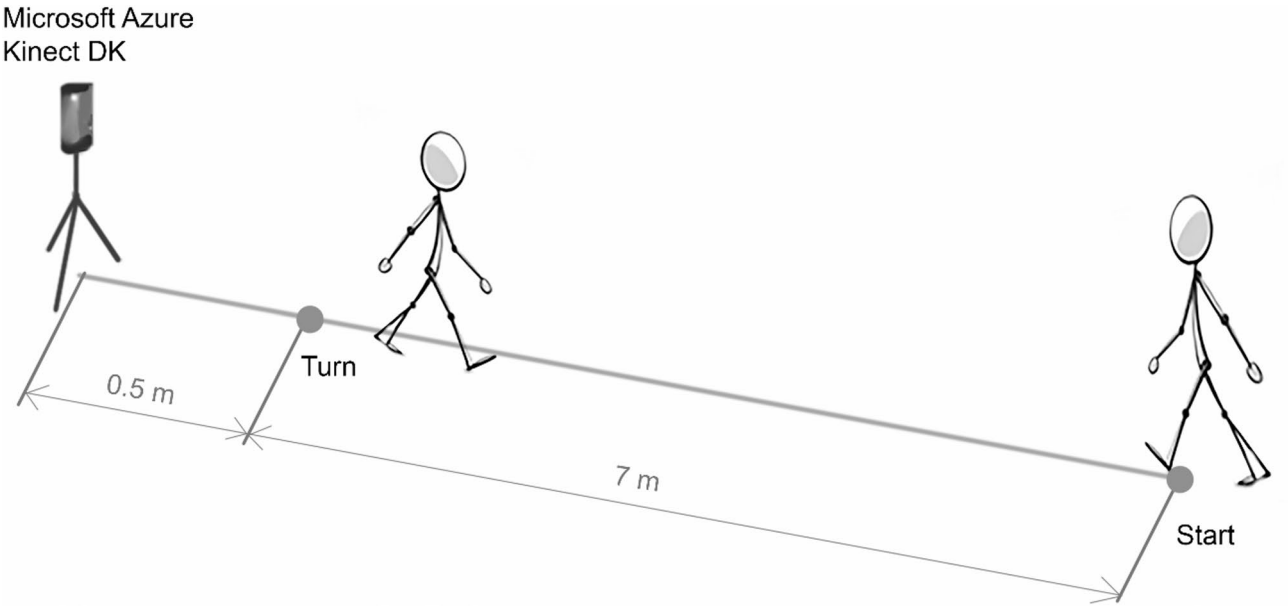

Fig. 1. Schematic representation of gait analysis protocol.

Decrements in dual-task walking were also expressed as a percentage of normal walking, commonly referred to as the dual-task cost (DTC = [dual-task walking – normal walking] / normal walking / 100)[53]. A higher DTC score indicates a greater cost of walking caused by performing the secondary task.

Data processing and analysis

Accelerometric data were processed using MT Manager Software (v. 4.2.1, Xsens Technologies, B.V., The Netherlands). Algorithms for accelerometric signal analysis and for calculating posture and gait variables were written in MATLAB R2020b (MathWorks Inc.,USA). The statistical analysis was performed using Python version 3.1, utilizing the Scipy library for its statistical functions. To assess the effect of the intervention on all variables, which were not normally distributed, we employed the Wilcoxon paired test. This non-parametric test was chosen to compare the differences between PRE and POST intervention values within each individual, thereby accommodating the non-normality of our data distribution. To evaluate the relationships between the effects of the intervention on postural and gait stability, we constructed a correlation matrix based on the exercise-induced changes (deltas) of each parameter which were calculated as the difference between PRE and POST intervention values. Subsequently, the Spearman correlation coefficient was utilized to explore the relationships between deltas of postural and gait parameters. Furthermore, we analyzed the correlation between PRE intervention stance time and exercise-induced changes in stance time during both normal and dual-task walking to better understand how the parameter behaves relative to its initial value, in the context of previous correlation analyses. We have also expressed the responsiveness of all postural and gait measures to the exercise intervention as the standardized response mean (SRM). The SRM was calculated as the mean change between PRE and POST intervention values divided by the standard deviation (SD) of the change. An SRM value of 0.20 indicates small responsiveness, 0.50 indicates moderate, and 0.80 indicates large responsiveness.

Results

Characteristics of the study population and the effects of exercise on anthropometric and clinical measures

Participant characteristics, including the anthropometric and clinical measures assessed PRE and POST intervention, are presented in Table 1. Body mass index, body fat and visceral fat content significantly decreased after the 4-month supervised aerobic-strength exercise intervention. The clinical state of PD as defined by the MDS-Unified Parkinson's Disease Rating Scale was also modulated by the intervention. Significant reduction of MDS-UPDRS-III score was present both in the ON and OFF medication states. The BBS score significantly increased in response to exercise intervention only when assessed in the OFF state, while the 10MWT and TUG test did not show significant change PRE versus POST intervention neither in ON nor in the OFF medication state.

Effects of exercise on postural stability

Supervised 4-month aerobic-strength exercise intervention influenced several postural parameters. This effect was particularly pronounced in the OFF medication state, standing on the foam support surface, independent of the visual cues. More specifically, exercise significantly reduced the mean frequency, sway path, and sway jerkiness of both the upper and lower trunk in conditions with eyes open. The mean frequency of both trunk parts sway as well as sway path and sway jerkiness of the lower trunk were also decreased while standing with eyes

closed. Sway area of the lower trunk significantly decreased as well, whether with visual information available or not. During postural conditions with intact proprioception from feet (i.e., while standing on a firm support surface), we found significantly reduced ST and L5 sway mean frequency during stance with eyes open, ST sway mean frequency and L5 sway path and sway jerkiness were also decreased when visual information was absent. Two postural parameters were also significantly reduced in the ON medication state: ST sway area in condition EO and L5 sway mean frequency in condition FEC (Table 2; Fig. 2).

Effects of exercise on gait performance

Spatiotemporal gait characteristics were analyzed PRE and POST exercise intervention. We observed significantly reduced stance time during dual-task walking in both the ON and OFF medication states. In the ON state, we also found a significant increase in walking speed during the dual-task walking (Table 3; Fig. 3).

Correlation patterns of exercise intervention's effects on postural and gait parameters

We examined the correlations between parameter changes (deltas) by subtracting PRE from POST intervention values. When evaluating relationships between the effect of intervention in L5 postural parameters and gait parameters in the ON medication state, we found multiple significant correlations of exercise-induced change in step length during dual-task walking with a change in L5 parameters measured while standing on a firm support surface. Also, stance time variability and stance time variability during DT walking were correlated with selected L5 parameters while standing on a firm support surface (Fig. 4).

Testing in the OFF medication state revealed an even greater number of significant correlations between exercise-induced changes in postural and gait parameters. There were correlations between the changes in dual-task walking parameters (i.e., DT step length variability, DT stance time, and DT stance time variability) and concurrent changes of L5 postural parameters measured while standing either on a firm or foam support surface. Moreover, the changes in stance time correlated with L5 parameters while standing on the firm or foam support surface, and changes in step length variability correlated with L5 parameters while standing on the foam (Fig. 5).

Significant correlations were also found between changes in the upper trunk stability (ST postural parameters) and gait parameters. In the ON medication state, we observed multiple positive correlations of the change in step length variability, most notably with the ST sway mean frequency while standing on foam. Moreover, the exercise-induced change of ST sway mean frequency negatively correlated with step length, and change in the ST sway area correlated with DT speed while standing on a firm support surface. In the OFF medication state, the change in step length variability also correlated with change in ST postural parameters while standing on foam. On the contrary, change in the stance time variability correlated with changes in several ST postural parameters measured while standing on a firm support surface. Complete results of correlation analyses showing relationships between effects of exercise in upper trunk postural measures and gait parameters can be seen in the Supplementary Fig. 2 and Supplementary Fig. 3.

Effect of dual-tasking

We observed distinct differences in the correlation pattern between exercise-induced change in stance time and changes in postural parameters depending on walking conditions - normal versus dual-task walking. In the OFF medication state, where most improvements in balance control were detected, opposite correlations of L5 postural parameters with stance time were found. Specifically, change in stance time during dual-task walking positively correlated with the change in L5 postural parameters, while change in stance time during normal walking negatively correlated with the change in L5 postural parameters (Fig. 6).

While significant improvements in stance time were observed during dual-task walking in both ON and OFF medication states, the same was not seen during normal walking. To visually illustrate the variability of this phenomenon, we plotted a graph showing exercise-induced changes in stance time (represented by arrows), sorted from the lowest to the highest baseline stance time values for normal walking (blue arrows); and from the highest to the lowest baseline stance time values for dual-task walking (red arrows). Figure 7a depicts these changes for each patient in the OFF medication state. Values of stance time during normal walking were significantly lower compared to stance time values during dual-task walking in both PRE ($p = 0.002$) and POST ($p = 0.001$) exercise intervention. During dual-task walking, we observed a significant exercise-induced reduction in stance time, especially in patients with initially higher values of stance time. Conversely, there was an increase in stance time during normal walking in some patients who had initially lower values of stance time. Moreover, a negative correlation between exercise-induced change in stance time and their baseline PRE intervention values (r=-0.66, $p < 0.001$) in the OFF medication state is depicted in Fig. 7b. The similar graph of changes in stance time in the ON medication state is presented in the Supplementary Fig. 4a, 4b.

Discussion

This study demonstrated that a supervised 4-month aerobic-strength exercise training induced medication-state- and task-dependent improvements in patients with Parkinson's disease, enhancing postural stability in the OFF medication state under multiple sensory conditions and during dual-task walking. Specifically, participants showed significant reductions in lower trunk sway path, jerkiness, and mean frequency while standing on a foam surface in the OFF state. These improvements were accompanied by clinically meaningful motor gains, as indicated by decreased MDS-UPDRS-III score and increased Berg Balance Scale score. Additionally, we observed adaptations in dual-task stance time, which decreased in both medication states.

Effect of exercise on upright stance

For the ON medication state, we observed a relatively weak effect of a 4-month exercise intervention on postural balance, with only 2 out of 8 parameters being decreased in response to intervention. Similar to our results, Allen

Condition	Eyes Open			Eyes Closed			Foam Eyes Open			Foam Eyes Closed		
	PRE	POST	P-value	PRE	POST	P-value	PRE	POST	P-value	PRE	POST	P-value
OFF medication												
L5_SA (m^2/s^5)	0.004 (0.003)	0.004 (0.004)	0.359	0.005 (0.002)	0.004 (0.005)	0.107	0.012 (0.009)	0.010 (0.008)	**0.048**	0.017 (0.011)	0.015 (0.009)	**0.048**
L5_MF (Hz)	0.570 (0.244)	0.473 (0.218)	**0.035**	0.604 (0.326)	0.541 (0.235)	0.524	0.507 (0.157)	0.439 (0.152)	**0.022**	0.552 (0.180)	0.482 (0.171)	**0.001**
L5_SP (m/s^2)	10.567 (4.824)	9.356 (4.099)	0.073†	12.073 (6.219)	10.337 (5.369)	**0.012**	16.601 (6.250)	13.714 (5.448)	**0.003**	20.934 (7.687)	18.557 (5.786)	**0.026**
L5_JERK (m^2/s^5)	1.822 (1.971)	1.492 (1.757)	0.073†	2.558 (3.262)	1.959 (2.677)	**0.030**	4.279 (3.608)	3.004 (3.088)	**0.003**	6.895 (6.083)	5.260 (4.018)	**0.018**
ST_SA (m^2/s^5)	0.008 (0.009)	0.008 (0.009)	0.804	0.009 (0.011)	0.009 (0.010)	0.510	0.019 (0.016)	0.016 (0.011)	0.252	0.026 (0.015)	0.025 (0.009)	0.978
ST_MF (Hz)	0.403 (0.164)	0.339 (0.126)	**0.022**	0.374 (0.154)	0.328 (0.159)	**0.048**	0.516 (0.156)	0.414 (0.161)	**0.030**	0.529 (0.188)	0.477 (0.218)	**0.035**
ST_SP (m/s^2)	12.262 (6.704)	10.965 (5.282)	0.073†	13.910 (8.899)	12.059 (6.123)	0.135	23.015 (10.514)	18.748 (7.292)	**0.004**	27.550 (10.287)	26.251 (8.261)	0.720
ST_JERK (m^2/s^5)	2.749 (3.734)	2.059 (2.431)	0.064†	3.952 (6.034)	2.586 (3.162)	0.107	9.357 (9.074)	5.878 (5.264)	**0.004**	12.439 (9.985)	11.044 (7.405)	1.000
ON medication												
L5_SA (m^2/s^5)	0.005 (0.005)	0.005 (0.005)	0.804	0.005 (0.006)	0.006 (0.006)	0.315	0.016 (0.022)	0.015 (0.013)	0.124	0.029 (0.037)	0.031 (0.039)	0.804
L5_MF (Hz)	0.517 (0.313)	0.471 (0.191)	0.720	0.547 (0.214)	0.487 (0.254)	0.252	0.489 (0.283)	0.461 (0.205)	0.934	0.574 (0.257)	0.511 (0.246)	**0.030**
L5_SP (m/s^2)	10.653 (7.263)	10.030 (5.886)	0.599	11.076 (6.481)	11.249 (7.165)	0.978	18.170 (16.694)	17.313 (10.742)	0.151	26.513 (21.877)	26.066 (21.416)	0.639
L5_JERK (m^2/s^5)	2.144 (3.657)	1.879 (2.687)	0.639	2.264 (3.292)	2.430 (3.969)	0.934	7.967 (16.323)	5.654 (8.338)	0.208	15.639 (27.579)	15.310 (27.566)	0.489
ST_SA (m^2/s^5)	0.011 (0.014)	0.007 (0.007)	**0.030**	0.011 (0.016)	0.011 (0.013)	0.188	0.024 (0.027)	0.026 (0.031)	0.524	0.042 (0.044)	0.049 (0.060)	0.826
ST_MF (Hz)	0.328 (0.151)	0.348 (0.151)	0.421	0.359 (0.145)	0.347 (0.175)	0.359	0.462 (0.209)	0.456 (0.168)	0.804	0.564 (0.219)	0.556 (0.295)	0.978
ST_SP (m/s^2)	12.471 (7.042)	11.445 (6.192)	0.188	13.293 (8.216)	13.187 (8.327)	0.934	23.351 (17.078)	23.654 (15.844)	0.489	34.811 (23.102)	35.930 (26.303)	0.561
ST_JERK (m^2/s^5)	2.708 (3.354)	2.298 (2.973)	0.303	3.315 (4.807)	3.329 (5.131)	0.978	11.279 (17.578)	11.101 (17.774)	0.524	24.558 (34.411)	26.493 (40.054)	0.934

Table 2. The effects of aerobic-strength exercise intervention on postural parameters in patients with Parkinson's disease. Data are shown as group mean (± SD). P-values indicate significance level showing differences between PRE and POST measurements, significant changes ($p < 0.05$) are in bold and trends ($p \geq 0.05$ and $p < 0.10$) are marked with †. L5 - data from accelerometer positioned at the 5th lumbar vertebra (lower trunk), ST - data from accelerometer positioned at the sternum (upper trunk), SA - sway area, MF - mean frequency, SP - sway path, JERK - sway jerkiness.

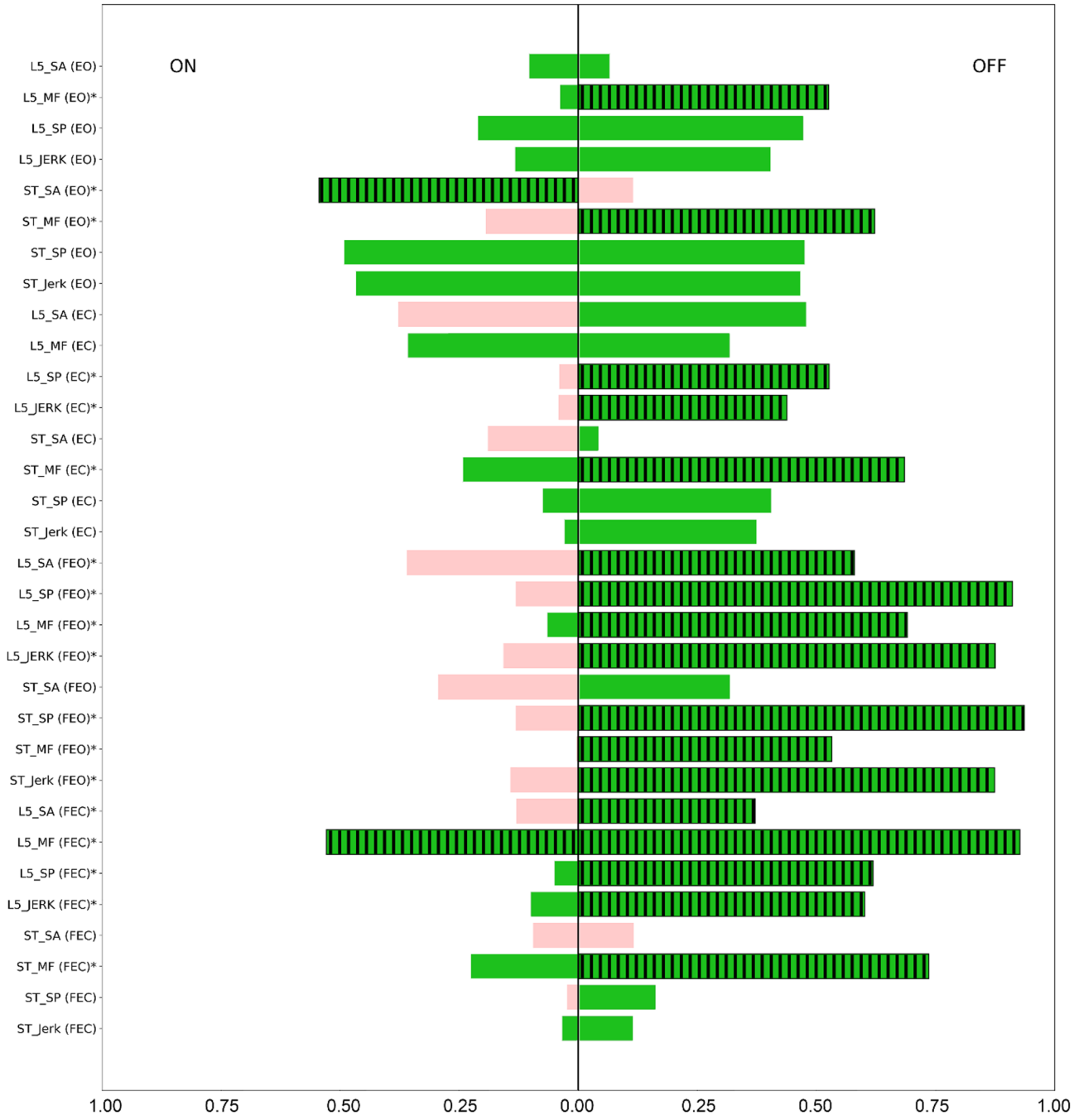

Fig. 2. Responsiveness of postural parameters to the 4-month aerobic-strength exercise intervention expressed as the standardized response mean. Green bars illustrate improvement (decrease) and pink bars illustrate deterioration (increase) of the postural parameters. Black stripes represent a significant change. Changes in the ON medication state are plotted on the left and changes in the OFF medication state are plotted on the right side of the graph. Asterisks indicate significant change of the parameter´s value POST intervention. L5 - data from accelerometer positioned at the 5th lumbar vertebra (lower trunk), ST - data from accelerometer positioned at the sternum (upper trunk), SA - sway area, MF - mean frequency, SP - sway path, JERK - sway jerkiness, EO - eyes open, EC - eyes closed, FEO - foam eyes open, FEC - foam eyes closed.

et al.[54] did not find a significant improvement of balance in PD patients after a 6-month exercise program, on the contrary, they found increased postural sway either when standing on the firm or on the foam support surface with eyes open POST exercise. Cabrera-Martos et al.[55] demonstrated improved dynamic balance after an 8-week stability core training program in patients with PD, however, their static balance remained unchanged after the intervention in all sensory conditions. On the other hand, some studies confirmed significantly improved static balance after progressive resistance exercise training which resulted in a decreased CoP sway path[35] or reduced CoP velocity[34] after the 8 and 12-week training programs, respectively.

Condition	Normal walking			Dual-task walking			Dual-task cost (%)		
	PRE	POST	P-value	PRE	POST	P-value	PRE	POST	P-value
OFF medication									
Step length (m)	0.510 (0.070)	0.521 (0.082)	0.252	0.475 (0.078)	0.475 (0.093)	0.847	-7.080 (7.009)	-9.229 (6.588)	0.188
Step length CV (%)	7.132 (1.608)	7.191 (1.459)	0.978	8.464 (2.105)	8.317 (2.785)	0.599	21.697 (29.714)	14.953 (24.110)	0.303
Stance time (s)	0.579 (0.028)	0.574 (0.021)	0.208	0.644 (0.055)	0.614 (0.039)	**0.026**	11.420 (10.743)	6.957 (6.781)	0.083†
Stance time CV (%)	9.472 (1.898)	9.303 (1.866)	0.890	9.078 (2.157)	8.974 (2.594)	0.762	-3.154 (17.603)	-2.380 (24.050)	0.890
Speed (m/s)	1.094 (0.153)	1.136 (0.174)	0.095†	0.930 (0.195)	0.980 (0.196)	0.121	-15.363 (11.030)	-14.079 (7.686)	0.277
ON medication									
Step length (m)	0.519 (0.070)	0.530 (0.074)	0.229	0.493 (0.081)	0.509 (0.076)	0.056†	-4.871 (10.643)	-3.387 (11.305)	1.000
Step length CV (%)	7.502 (1.751)	6.861 (1.186)	0.229	8.063 (1.914)	7.367 (1.377)	0.169	8.319 (16.686)	8.501 (17.583)	0.978
Stance time (s)	0.563 (0.045)	0.563 (0.040)	1.000	0.653 (0.040)	0.632 (0.035)	**0.048**	16.633 (11.497)	12.672 (9.924)	0.188
Stance time CV (%)	9.910 (2.757)	10.433 (2.760)	0.229	9.083 (2.135)	9.078 (1.280)	0.847	-4.406 (24.828)	-8.878 (20.451)	0.561
Speed (m/s)	1.141 (0.167)	1.176 (0.136)	0.359	0.953 (0.191)	1.028 (0.159)	**0.018**	-16.144 (13.189)	-12.413 (10.964)	0.252

Table 3. The effects of a 4-month aerobic-strength exercise intervention on gait parameters in patients with Parkinson's disease. Data are shown as group mean (± SD). P-values indicate significance level showing differences between PRE and POST measurements, significant changes ($p < 0.05$) are in bold and trends ($p \geq 0.05$ and $p < 0.10$) are marked with †. CV - coefficient of variability.

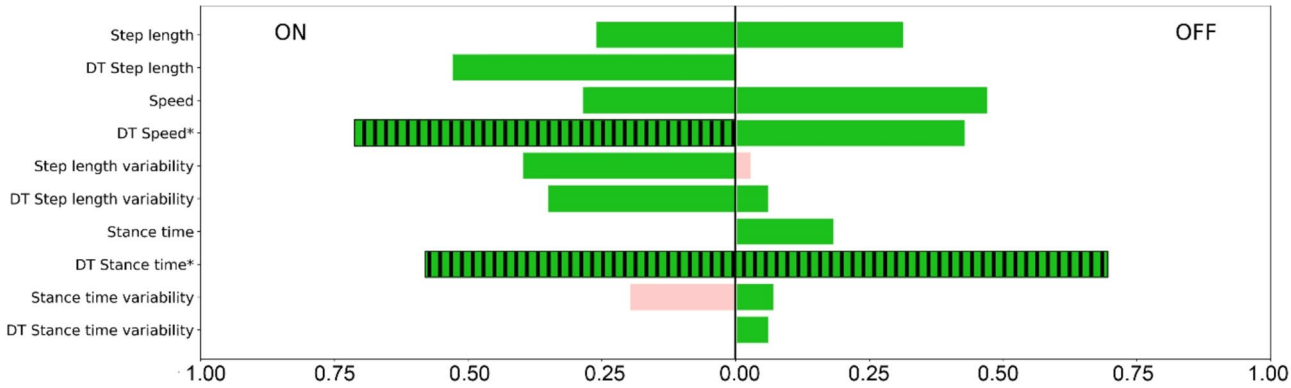

Fig. 3. Responsiveness of gait parameters to the 4-month aerobic-strength exercise intervention expressed as the standardized response mean. Green bars illustrate improvement (increase in step length, speed; decrease in stance time and all variability parameters) and pink bars illustrate deterioration of the gait parameters. Black stripes represent a significant change. Changes in the ON medication state are plotted on the left and changes in the OFF medication state are plotted on the right side of the graph. Asterisks indicate significant change of the parameter´s value POST intervention. DT - dual-task walking.

Our results unequivocally demonstrate an improvement of postural balance as measured in the OFF medication state. We objectified significant changes PRE versus POST exercise intervention in multiple parameters and testing conditions. Previous reports indicated that PD patients have impaired central processing of somatosensory and vestibular information, resulting in compromised sensory reweighting and increased reliance on vision to maintain balance[56–59]. Significantly reduced postural sway POST intervention, especially during conditions on the foam, suggests that aerobic-strength exercise may positively affect the ability to reorganize the sensory contribution to balance control and quickly adjust when sensory conditions are altered[32]. The reduction in nearly all trunk sway parameters while standing on a foam support surface, regardless of visual condition, indicates improved regulation of sensory integration for postural control under steady-state conditions. Furthermore, reduced trunk jerkiness suggests more active postural corrections[37], leading to reduced trunk axial rigidity[60].

Regarding the effect of exercise on postural stability, several recently published reviews[61,62] and meta-analyses[63,64] include studies that evaluated the effectiveness of different exercises in PD patients with and without levodopa treatment, but did not look at differences in postural balance after exercise intervention in relation to medication intake. Other meta-analyses[65,66] focus on the effect of exercise without any mention of antiparkinsonian medication status. To the best of our knowledge, studies that evaluate the effects of exercise in connection with the medication state are completely lacking.

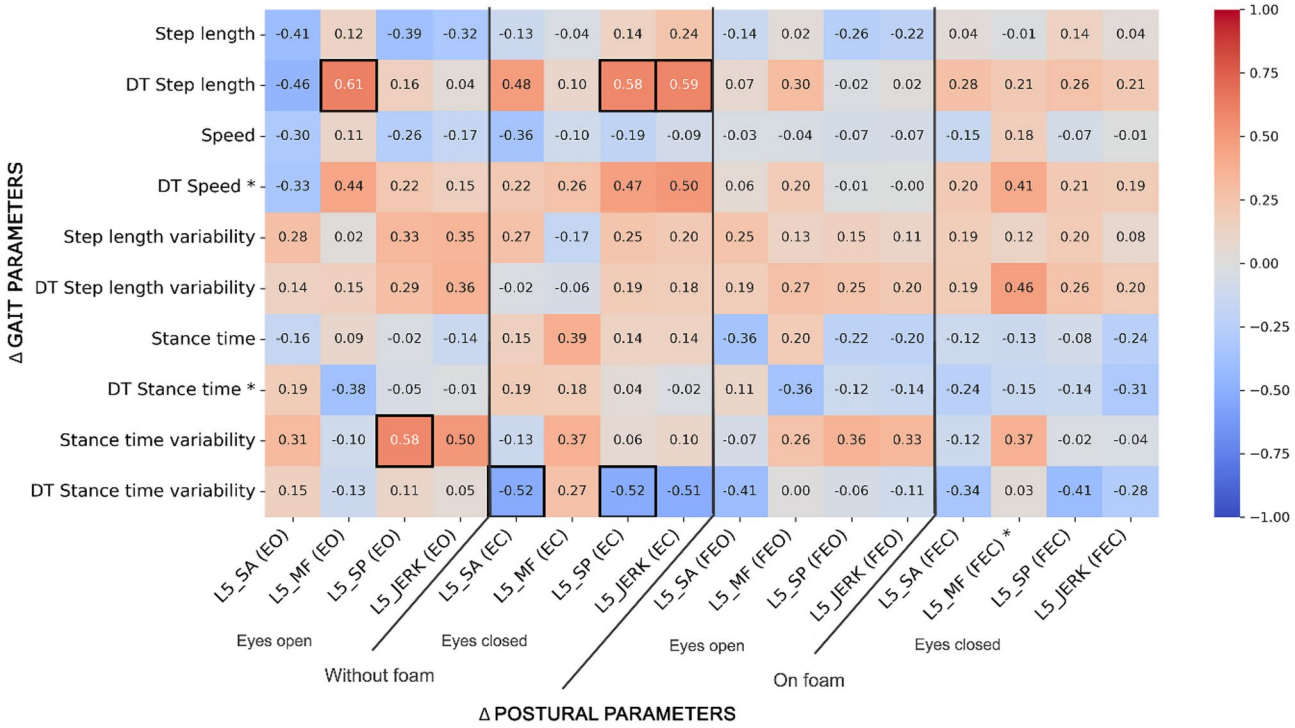

Fig. 4. Correlation patterns of exercise-induced changes (deltas) between L5 postural parameters and gait parameters as measured in the ON medication state (bolded squares indicate significant correlation with $p < 0.05$, asterisks indicate significant change of the parameter´s value POST intervention). L5 - data from accelerometer positioned at the 5th lumbar vertebra (lower trunk), SA - sway area, MF - mean frequency, SP - sway path, JERK - sway jerkiness, EO - eyes open, EC - eyes closed, FEO - foam eyes open, FEC - foam eyes closed, DT - dual-task walking.

Effect of exercise on gait

We observed significantly reduced stance time during dual-task walking in both the ON and OFF medication states. The improvement of dual-task walking speed was only visible when measured ON medication. This could be partially explained by the effect of levodopa treatment, which has been shown to improve pace-related metrics and worsen postural sway[25,67]. Previous research has demonstrated increased walking speed after the exercise program[68,69] as strength training also improved gait initiation[32]. Increased cadence (but not speed) has prevailed even in a long-term (2 years) study with PD patients performing strength, balance and stretching exercises in both ON and OFF medication states[70]. In our study, we did not find improved performance in normal walking; however, greater improvements were observed in dual-task walking, possibly due to the more challenging conditions imposed by the dual-task on walking[32]. The lack of detected significant changes during normal walking could be attributed to the low number of participants with good mobility before the exercise intervention began. This statement is supported by high performance in the 10MWT in both ON (8.07 ± 0.38 s) and OFF medication states (8.46 ± 0.27 s) as well as in the TUG test (ON state: 8.79 ± 0.50 s, OFF state: 9.29 ± 0.61 s) PRE intervention. The absence of improvements in normal walking, as well as in the 10 MWT and TUG may be due to a ceiling effect.

Posture and gait interplay

A key focus of our study was to compare the effects of exercise on static posture and gait. We explored the relationships between exercise-induced changes in postural and gait parameters. Several significant correlations were found, suggesting possible links between static and dynamic postural control, as well as the influence of exercise intervention on these parameters. Notably, correlations between stance time and postural parameters in the OFF medication state stood out, reflecting the significant impact of exercise intervention on both postural measures and dual-task stance time. As expected, we found positive correlations between dual-task stance time and postural parameters. However, contrary correlations emerged between stance time during normal walking (without dual-task) and postural parameters. We observed that individuals with initially higher stance time during dual-task walking showed more pronounced improvements (shortening of stance time) compared to those with initially lower stance time. Additionally, some PD patients exhibited prolonged stance time during normal walking as a result of the exercise intervention, and there was a linear correlation between PRE intervention stance time and the subsequent changes in stance time following the exercise intervention.

Based on these results we propose a hypothesis that there is an optimal zone where patients maintain balance. During walking without any added challenges, two states can be defined: (a) the patient is stable, and (b) the patient is unstable. The stance time is within the optimal zone if the patient is stable. If unstable,

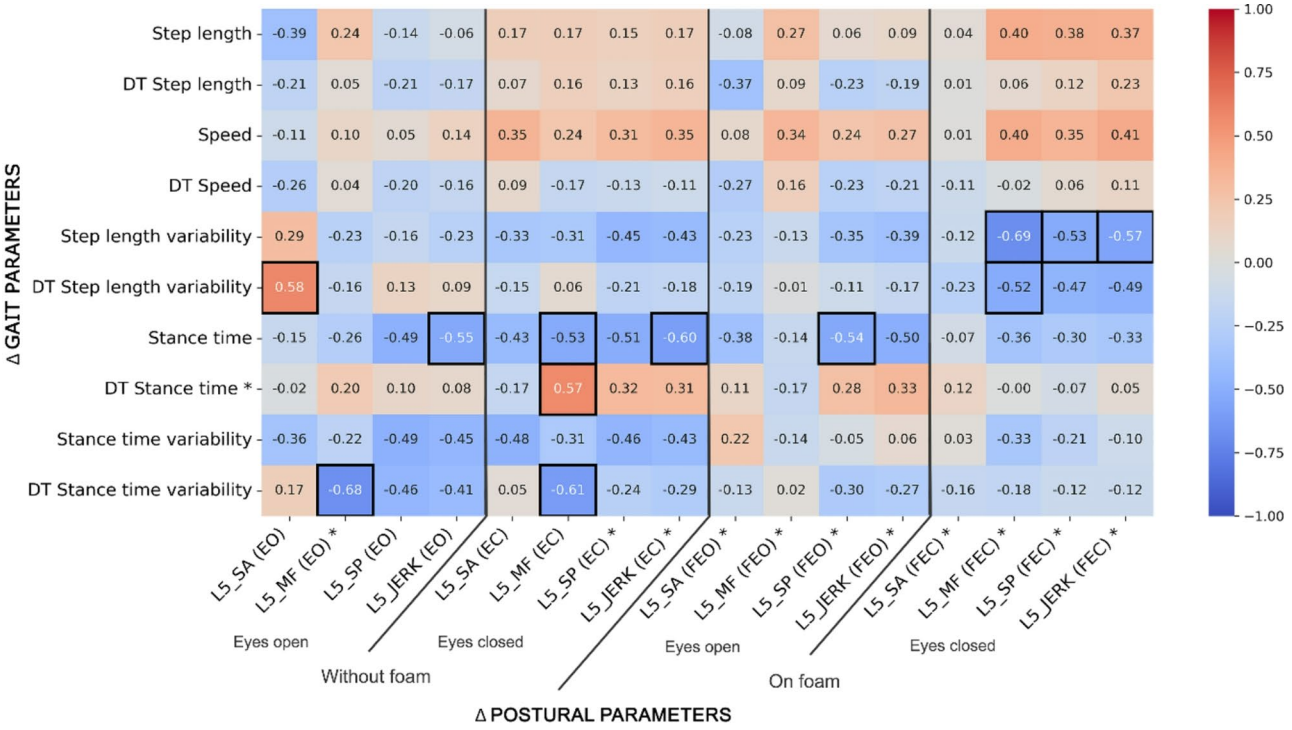

Fig. 5. Correlation patterns of exercise-induced changes (deltas) between L5 postural parameters and gait parameters as measured in the OFF medication state (bolded squares indicate significant correlation with $p < 0.05$, asterisks indicate significant change of the parameter´s value POST intervention). L5 - data from accelerometer positioned at the 5th lumbar vertebra (lower trunk), SA - sway area, MF - mean frequency, SP - sway path, JERK - sway jerkiness, EO – eyes open, EC – eyes closed, FEO – foam eyes open, FEC – foam eyes closed, DT – dual-task walking.

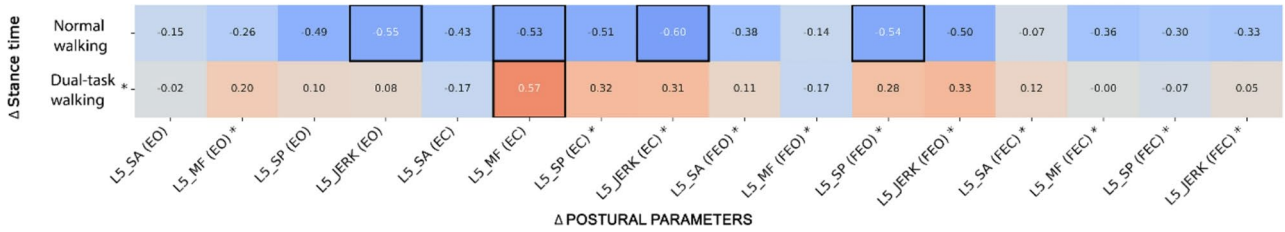

Fig. 6. Correlations of exercise-induced changes (deltas) in stance time during normal and dual-task walking with changes in L5 postural parameters in the OFF medication state (bolded squares indicate significant correlation with $p < 0.05$, asterisks indicate significant change of the parameter´s value POST intervention). L5 - data from accelerometer positioned at the 5th lumbar vertebra (lower trunk), SA - sway area, MF - mean frequency, SP - sway path, JERK - sway jerkiness, EO – eyes open, EC – eyes closed, FEO – foam eyes open, FEC – foam eyes closed.

the patient compensates by increasing their step frequency, leading to a stance time lower than their optimal zone. Improved postural stability (found POST exercise intervention) could be represented by two seemingly opposing outcomes: a stable patient may decrease stance time as their optimal zone shifts, while an unstable patient may increase stance time, bringing them closer to their previously unachieved optimal zone. Adding a cognitive task to walking (dual-task) takes the patient out of this comfort zone, causing them to slow down their gait and remain longer in the stance phase despite losing speed. The improvement in stability therefore decreases the stance time leading the patient to their optimal zone (Fig. 8).

Previous studies have shown that PD patients have a longer stance time with higher maximum vertical force applied to the ground compared to the healthy population, which is also shifted later in the overall gait cycle[71]. This indicates the longer time and effort patients put into stabilization compared to healthy persons. An increased stance phase duration is also associated with a risk of falls in the elderly[72]. It is therefore natural to expect stance time to decrease with improved postural stability. However, studies on the effect of exercise show either a decrease in stance phase duration or ambiguous results. For example, in the study by Rennie

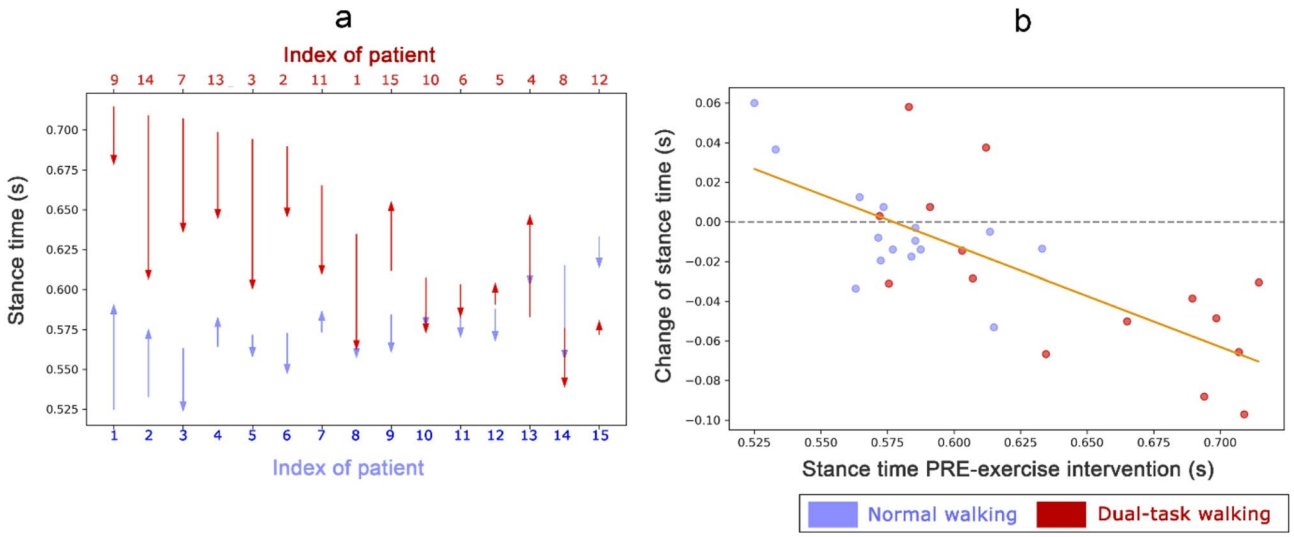

Fig. 7. **(a)** Exercise-induced changes in stance time in the OFF medication state. Arrows indicate changes in stance time values from PRE to POST exercise intervention in individual patients (index of patient 1–15). Red arrows indicate individual changes in stance time in dual-task walking and are sorted by the baseline stance time values in descending order. Blue arrows indicate changes in stance time in normal walking and are sorted by the baseline stance time values in ascending order. Note that red and blue arrows in the same column (on the x-axis of the graph) do not represent the same patient, as red and blue arrows are sorted by descending and ascending order, respectively. **(b)** Correlation of stance time measured PRE intervention with exercise-induced changes in stance time combining values from both normal (blue) and dual-task (red) walking (r=-0.66, $p < 0.001$) in the OFF medication state.

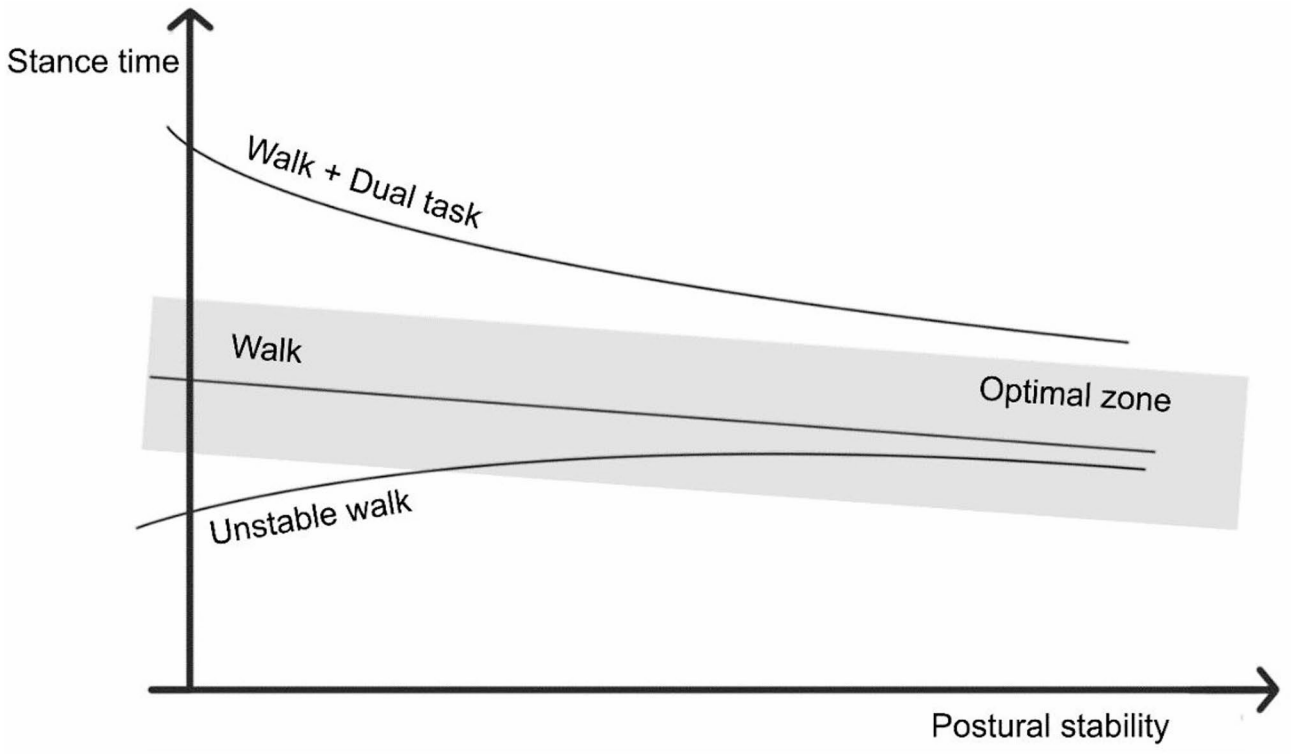

Fig. 8. A hypothesized model of the stance time dependent on the postural stability.

et al.[73], a reduction in stance phase duration, increased speed, and longer stride length were observed after balance training in the ON medication state. In another study, authors examined the effect of dancing by measuring walking on flat and uneven surfaces in the ON medication state[74]. While walking on a flat surface, they showed increased speed, cadence, and stride length in both single and dual-task conditions, walking on an uneven surface (with wooden blocks hidden under the carpet) yielded different results. On an uneven surface, significant changes in speed, cadence, and stride length were observed only under dual-task conditions. Patients demonstrated a shortened stance time during dual-task walking, whereas walking without a dual-task resulted in a prolonged stance phase. These results align with our hypothesized model. An uneven surface might cause patients discomfort - in terms of our model, it puts the stance time under the optimal zone, where the patient feels unstable. Improvement should, therefore, lead toward prolonged stance phase duration. The change in the opposite direction is thus visible only in dual-task walking. Conditions with dual tasks are commonly used for testing PD patients, where cognitive resources compete between postural stability and task-solving. According to Yogev-Seligmann et al.[53], prioritization depends on postural reserve and hazard estimation with their interplay affecting task prioritization strategies. Intact postural reserve enables focusing on the cognitive task even when the postural threat is considerably high. Individuals who are cognitively intact (high hazard estimation), but have low postural reserve, such as vestibular patients or paraparetic individuals, will probably focus on the postural task even in relatively low postural threat conditions, being aware of their self-limitations and environmental hazards. Alternatively, individuals with high or low postural reserve, but poor hazard estimation, such as cognitively impaired patients with PD or older adults, might maintain their focus on the cognitive task even when the postural threat increases, exposing themselves to the risk of falling by inappropriately using a posture-second strategy. Our proposed model shows gait from an opposite perspective: how different conditions affect stance time based on postural stability. In our study, it seems that improvements in postural reserve through aerobic-strength exercise influenced gait patterns—particularly stance time—in different ways depending on the walking condition. Specifically, the correlations between changes in postural parameters and gait differed between single- and dual-task walking. During dual-task walking, PD patients naturally tended to slow down, resulting in a more stable gait. Improved postural reserve allowed them to maintain better stability without needing to reduce their walking speed as much. In contrast, during normal walking without the added challenge of a cognitive task, gait instability was more apparent in some patients. Interestingly, we observed that some individuals appeared to compensate for their instability by increasing walking speed. Our hypothesis suggests that improvement of postural balance in PD patients could lead to reduced stance time and faster walking, though the opposite results - an increased stance time - may also be a result of improved stability in patients with lower levels of postural stability.

Limitations

While this research provides valuable insights, it is important to consider its limitations. The main limitation is the sample size and the limitation of including only patients in the early to middle stages of the disease course who were able to regularly participate in the exercise intervention. As such, the participants were in good physical shape prior to the study, limiting the sensitivity of certain tests (10MWT, TUG, walking) by a ceiling effect. We didn't compare the effects of the aerobic-strength exercise intervention to an active control group which would be subjected to stretching exercise. We have initially attempted to recruit patients into the control group, but ethical reasons and low completion rate for individuals enrolled in this group prevented us from doing so. Furthermore, the selected accelerometric data for postural analysis and gait measurements may not capture the full complexity of postural and gait control mechanisms. In this study, we compared the effect of dual-task on walking and we did not measure the effect of dual-task on standing posture. In addition, the correctness of participants' responses during dual-task walking was not assessed. Future research in larger cohorts employing multi-modal assessment tools is necessary to corroborate results of this study.

Conclusion

In conclusion, our study highlights the distinct effects of a supervised 4-month exercise intervention on postural control and gait in PD patients across medication states. Results indicate substantial improvement in postural balance in the OFF medication state, especially when proprioceptive feedback is challenged. Gait improvements were notable during dual-task walking but were not significant during normal walking. Opposite correlation patterns between exercise-induced changes in postural parameters and stance time, along with different effects during normal and dual-task walking suggest, that to capture interrelations between balance and gait parameters, measurements should be performed in the OFF medication state and a dual-task condition should be applied. We have developed and validated the model determining the individual optimal zone for stance time (walking speed) and capacity of regular exercise intervention to shift the zone of comfort (enhanced functional walking capacity), allowing patients with Parkinson's disease to maintain their balance without the loss of movement speed. Dual-task conditions put cognitive resources under pressure, and the balance is maintained by sacrificing the speed. However, lower stance time during walking without additional challenges can also indicate poor balance. In that case, the improvement in postural control can result in prolonging the stance time. These findings pave the way for a more in-depth understanding and individualized motor symptom management in Parkinson's disease and highlight the role of personalized exercise interventions in improving patient's outcomes and clinical state.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Project conception, design and organization (B.U.); participants recruitment (Z.K., I.S., P.V.); software development (P.M., Z.K., M.T.N.); clinical examinations (Z.K., L.S., I.S., Z.U., J.U., B.U.); exercise intervention design and execution (L.S., V.T., P.K., V.L.); gait measurements (P.M., Z.U.); balance measurements (D.B., J.K.); data management, analysis and interpretation (P.M., D.B., Z.K., K.M.M., O.M., M.T.N., J.U., J.K.); statistical analysis (P.M., J.K.), drafting of manuscript (P.M., J.K.), revising the manuscript critically for important intellectual content (D.B., Z.K., I.S., P.V., J.U., B.U.). All authors read and approved the final version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

The experimental protocol was approved by the ethics committee of the University Hospital Bratislava and the ethics committee of Bratislava Region, and complied with the ethical standards of the Helsinki Declaration of 1964 (2013 revision). All participants provided written informed consent prior to the study entry, including disclosure of the data obtained.

Additional information

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