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The impact of loneliness on balance learning ability in aging patients with Parkinson's disease

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Abstract

Objective Loneliness is highly prevalent among patients with Parkinson's disease (PwPD) and, through complex body-brain interactions, increases their vulnerability to health issues, including balance impairments. Despite extensive evidence linking loneliness to cognitive-motor dysfunctions, the direct impact of loneliness on motor learning, particularly dynamic balance learning, has not been comprehensively examined. As the first study in this field, our research investigates the effect of loneliness on the ability to learn dynamic balance in PwPD, addressing a critical research gap in this domain.

Methods This study was conducted over six months with the participation of sixty volunteers divided into three distinct groups: 20 PD patients who reported loneliness (loneliness-positive group), 20 PD patients who did not report loneliness (loneliness-negative group), and 20 healthy individuals as the control group. Participants were matched for sex, age, and body mass index (BMI) and were recruited from hospitals and specialized movement disorder clinics. We utilized standardized instruments, including the Mini Balance Evaluation Systems Test (MiniBESTest) to assess balance performance, the de Jong-Gierveld Loneliness Scale (DjG)/ the Three-Item Loneliness Scale (TILS/ the Social and Emotional Loneliness Scale for Parkinson's Disease (SELSA-PD) to assess loneliness levels, the Rosenberg Self-Esteem Inventory (RSI) to assess self-steem, and the Multidimensional Scale of Perceived Social Support (MSPSS) to assess social support in one day before performing balance learning task. Additionally, balance learning was evaluated using a stabilometer, and parameters such as learning rate, learning curve slope, and short- and long-term memory were analyzed.

Results The results indicated that PwPD in the loneliness-positive group exhibited poorer balance performance (MiniBESTest) and higher scores on various loneliness scales, including DjG, TILS, and SELSA-PD. Additionally, this group did not demonstrate balance learning potential (learning rate and slope) compared to the other groups.

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In contrast, PD patients in the loneliness-negative group showed improvement in the early stages of balance learning (Block1 vs. Block3: $p = 0.001$; Block1 vs. Block4: $p = 0.001$; Block1 vs. Block5: $p < 0.001$; Block2 vs. Block5: $p = 0.014$).), while the control group exhibited continuous improvement ($p = 0.00$). Both the loneliness-negative and control groups retained their balance skills in both short-term and long-term assessments ($p > 0.05$).

Conclusion This study is the first to directly examine the impact of loneliness on dynamic balance learning in PwPD. The findings revealed that loneliness can act as a significant inhibitory factor in balance rehabilitation for these patients. The results underscore the importance of designing targeted interventions to reduce feelings of loneliness to enhance balanced learning. Furthermore, the study paves the way for future research to investigate the underlying neural mechanisms and explore the effects of social and psychological interventions on improving motor learning in these patients.

Keywords Learning, Memory, Motor Learning, Parkinson's Disease, Loneliness

Article summary

Loneliness is common among patients with Parkinson's disease (PwPD) and is associated with serious health risks, including balance impairments and an increased risk of falls. However, its impact on motor learning, an essential component of neurorehabilitation, has not been comprehensively examined. As the first study in this area, the present research investigates the effect of loneliness on dynamic balance learning in these patients, addressing a critical research gap in this field.

In this study, 20 PwPD experiencing loneliness (loneliness-positive), 20 PwPD without feelings of loneliness (loneliness-negative), and 20 healthy individuals as a control group participated. Balance learning was assessed using a stabilometer, and the ability to acquire and retain balance-related skills was compared between PD patients with and without loneliness.

The results revealed that PD patients experiencing loneliness had poorer balance performance, scored higher on loneliness scales, and exhibited significant deficits in balance learning compared to their non-lonely counterparts. These findings underscore the need for interventions targeting loneliness to enhance balance learning in PwPD.

Introduction

Acquisition and retention of balance skill, i.e., balance learning, are crucial for the neurorehabilitation of patients with Parkinson's disease (PwPD) [1]. PwPD exhibit impaired motor learning, affecting both upper and lower limb functions. Studies demonstrate learning deficits in retaining upper limb writing skills [2, 3], forced symmetrical step-taking, and automatic protective stepping responses [4–6] to control center of mass (COM) displacement in the backward direction [4]. Identifying factors that influence motor learning is essential for designing effective rehabilitation strategies, particularly for balance skills due to their fundamental roles in gait, activities of daily living, and fall prevention. Loneliness may represent a key factor in this context.

Loneliness (or perceived social isolation) and social isolation, although often used interchangeably, are distinct concepts that reflect different aspects of social interactions. Loneliness is a subjective experience that arises when an individual perceives a significant gap between their desired social and emotional connections and what they actually experience [7, 8]. In contrast, social isolation is an objective condition characterized by a measurable reduction or absence of social interactions [7, 8].

Studies have shown that loneliness, often resulting from social isolation [9], can have detrimental effects on both mental and physical health and is recognized as a potential risk factor for neurodegenerative diseases, including Parkinson's disease (PD) [10]. Individuals who experience loneliness have an increased risk of PD, independent of genetic, behavioral, social, and clinical risk factors [10]. Loneliness is likely linked to elevated PD risk through metabolic, inflammatory, microglia-mediated neuroinflammation, and neuroendocrine pathways [11–13]. Notably, loneliness may be directly associated with neuropathological markers such as α-synuclein and neurofilament light chain, which require further investigation. Additionally, loneliness could increase PD risk by diminishing resilience to neurodegenerative processes that contribute to disease development [10]. The high prevalence of loneliness among PwPD has raised significant concerns. Research indicates that between 24.1% and 53.8% of PwPD experience some degree of loneliness [14], which is associated with increased severity of both motor and non-motor symptoms [15]. Patients experiencing loneliness report approximately 55% greater symptom severity, including significant balance impairments [16]. It is also associated with cognitive declines in domains critical for motor learning—such as executive function, working memory, and recall [17–19] —suggesting that loneliness may indirectly compromise motor

learning capacity in PwPD, a hypothesis that remains insufficiently explored.

While human research on loneliness and motor learning is limited, animal studies provide compelling evidence that social isolation impairs neural mechanisms fundamental to motor learning. For instance, social isolation disrupts synaptic plasticity [20], reduces dendritic spine density [21], and decreases the number of synapses and myelin-related proteins expression [22], resulting in deficits in various memory types, including contextual fear and long-term memory [20, 23, 24].

Previous studies indicate that the basal ganglia, cerebellum, and hippocampus are key brain structures whose dysfunction and structural alterations are implicated in both loneliness [11, 22, 25, 26] and motor learning deficits [27–29], particularly in PD. Loneliness has been associated with volumetric reductions in basal ganglia structures such as the putamen and globus pallidus, which likely reflect diminished social reward processing and contribute to cognitive and motor decline [30]. Dysfunction of the basal ganglia impairs early consolidation, long-term retention, and the development of automaticity in motor learning [28, 29].

Increased cerebellar volume and altered functional connectivity observed in individuals prone to loneliness suggest enhanced cerebellar involvement in processing social and emotional stimuli [31]. The cerebellum also plays a critical role in motor planning, memory stabilization, and movement adaptation [32, 33]. In PD, cerebellar dysfunction compromises motor learning, particularly dynamic balance [27, 34–36].

Additionally, the hippocampus exhibits structural and functional changes linked to loneliness and social isolation [22]. Heightened hippocampal responses to social threat stimuli and volume reductions correlate with increased loneliness and cognitive deficits [22]. The hippocampus is essential for memory consolidation and cognitive regulation [37, 38]. In PD, hippocampal impairment disrupts motor learning consolidation, thereby exacerbating difficulties in acquiring and retaining new motor skills [27, 34–36].

Collectively, structural and functional alterations in these regions may diminish patients' ability to learn and adapt motor skills, which are crucial for maintaining balance.

Despite strong evidence from animal models linking loneliness to disrupted motor learning mechanisms and overlapping brain regions [39], the specific effects of loneliness on balance learning and motor memory in humans remain poorly understood. Given the challenges PwPD already face in balance learning and the potential exacerbating influence of loneliness, elucidating these relationships is crucial. A deeper understanding could inform the development of optimized neurorehabilitation interventions targeting balance, thereby reducing fall risk. Integrating social and psychological factors within rehabilitation paradigms, alongside pharmacological and physical treatments, may enhance overall patient outcomes and quality of life.

This study aims to address this gap by investigating the impact of loneliness on balance learning and memory in PwPD. Additionally, given the common comorbidities of anxiety and depression in PD and its close relationship with loneliness, we examined their potential confounding effects on loneliness-related impairments in balance learning. We hypothesize that loneliness negatively affects both the acquisition and retention of dynamic balance skills in this population. Furthermore, we propose that anxiety and depression do not significantly mediate the detrimental effects of loneliness on balance learning and memory in PwPD.

Methodology

Sample size

To determine the sample size, an initial power analysis was conducted with a Type I error probability of 0.05, a Type II error probability (statistical power) of 0.80, and an expected dropout rate of 10%. The results indicated that, based on a pilot study measuring the standard deviation of balance maintenance time, 20 participants were required for each group.

Participants

A total of 40 PwPD, including 26 men and 14 women, with a mean age of 70.53 years (± 5.66) with range of 65 to 80, were recruited over a six-month period from rehabilitation and movement disorder clinics. The diagnosis was confirmed based on the UK Parkinson's Disease Society Brain Bank Diagnostic Criteria [40].

Participants were included in the study if they met the following criteria: the ability to stand unassisted for at least one hour—this requirement was established based on previous studies related to balance tasks [41, 42] and our pilot study. The pilot study demonstrated that patients who could stand for less than one hour often lacked the ability to perform the test adequately. Prior to testing, participants were asked to engage in activities of daily living for one hour; individuals unable to do so were excluded from the study. Additional inclusion criteria included a diagnosis of mild to moderate Parkinson's disease (stages I to III on the Hoehn and Yahr (H&Y) scale), a postural instability score of ≤ 1 on the Unified Parkinson's Disease Rating Scale (UPDRS), no history of falls in the past 12 months, and no prior experience using a stabilometer.

The exclusion criteria included the following: a history of deep brain stimulation, lower limb freezing, as assessed by item 1 of the New Freezing of Gait Questionnaire and

clinically confirmed by a neurologist (patients who did not meet both conditions were excluded), other neurological disorders, orthopedic conditions affecting balance, cognitive impairment (a score below 24 on the Montreal Cognitive Assessment (MoCA)) [43], severe anxiety or depression (Hospital Anxiety and Depression Scale [HADS-A/D] score > 7) [44] or reporting by patients and their family, a history of musculoskeletal surgery, medication changes within one month prior to or during the study, and substance use—including alcohol, tobacco, opium, glass, heroin, or smoking within the past year. Participants who experienced motor fluctuations during the test or learning process were excluded from the study. Additionally, those who altered their foot position or leaned on the harness during the balance learning task were excluded. Given that the balance task requires standing dynamic balance and weight shifting, and considering that pain can affect movement, motor control, and learning, we included pain assessment and evaluated group differences [45]. Participants reporting chronic or acute pain conditions were also excluded.

PwPD were divided into two groups based on the De Jong Gierveld Loneliness Scale (DjG): 1) Loneliness-negative group: Score less than 3 ($n = 20$), 2) Loneliness-positive group: Score 3 or higher ($n = 20$). The presence of loneliness was also confirmed by a psychiatrist [46].

The groups were matched for sex, age, and body mass index (BMI). To identify the more affected side of the body, the sum of lateralized scores from the UPDRS Part III (items 20–26) was used [47]. The levodopa equivalent dose (LED) was calculated using the formula provided by Tomlinson et al. [48].

During the study, none of the PwPD were receiving anxiolytic, antidepressant, or anti-inflammatory medications (due to their potential effects on loneliness), and no interventions targeting loneliness had been administered. All patients were responsive to levodopa treatment. None of the participants engaged in rehabilitation or exercise programs throughout the study.

Additionally, 20 healthy individuals, matched with the patients in terms of sex, age, and BMI, were included in the study as the control group. These individuals had no history of falls in the past year and did not suffer from any musculoskeletal or neurological disorders, anxiety or depression (HADS-A/D ≤ 7) [44], loneliness (DjG < 3), or cognitive impairment (MoCA ≥ 24) [43].

Clinical assessments

Given the multifactorial nature of loneliness and its association with various motor and non-motor factors, this pioneering study conducted multiple clinical assessments, including evaluation of the contributory effects of anxiety and depression. In this study, the following measures were used to assess balance function (Mini Balance Evaluation Systems Test (MiniBESTest) [49]), executive function (Trial Making Test (TMT) part A and B), pain (visual analog scale for pain (VAS-p)), fatigue (Fatigue Severity Scale (FSS) [50] / Parkinson's Disease Fatigue Scale (PDFS) [51]), anxiety (Beck Anxiety Inventory (BAI) [52]/ State-Trait Anxiety Inventory (STAT) [53]), depression (Beck Depression Inventory (BDI) [54]), falling (Falls Efficacy Scale-International (FESI) [55]), sleep quality (Pittsburgh Sleep Quality Index (PSQI) [56] / sleep duration after training and before retention), QoL (Parkinson's Disease QoL Questionnaire (PDQ-39) [57]), loneliness (DjG [58]/ Three-Item Loneliness Scale (TILS)) [59]/ the Social and Emotional Loneliness Scale for Adult-PD version (SELSA-PD)), self-esteem (Rosenberg Self-Esteem Inventory (RSI) [60]), and social support (Multidimensional Scale of Perceived Social Support (MSPSS) [61]). The cause for selection of these were due to their effect on balance learning and loneliness and to assurance of solely investigated the effect of loneliness on balance learning in PwPD.

All tests were conducted on a single day prior to the balance learning task, with participants provided 3–5 min of rest—or longer if needed—between assessments to minimize fatigue.

The authors emphasize that all procedures conducted in this study adhered to the principles of the Declaration of Helsinki (1975) and its revised version (2013), as well as the ethical guidelines established by relevant national and institutional committees for human studies. Participants also provided written informed consent before their involvement in the study. Additionally, this study was approved by the Ethics Committee of Iran University of Medical Sciences (IR.IUMS.REC.1402.497).

Balance learning task

In this study, balance learning was assessed using a stabilometer, a highly ecologically valid tool for evaluating balance [62]. This instrument requires participants to perform an attention-demanding balance task that involves continuous postural adjustments by shifting the center of mass (COM) in the medio-lateral direction [63].

Participants stood on a stabilometer (a 15-degree tilting platform) while wearing a safety harness and attempted to keep it as level as possible during multiple balance trials. The initial foot position in the first trial was recorded as the comfortable stance and remained constant throughout the test. In each trial, participants were required to maintain the platform within ± 5 degrees of the horizontal position for 30 s, with balance maintenance duration recorded using a millisecond timer. The Role of Aquaporin-4 in Freezing of Gait and Dynamic Balance Learning in Parkinson's Disease [41, 64]. After each trial, participants received rigid feedback on their

balance maintenance duration. Additionally, stabilometer calibration was conducted individually before testing began.

A pilot study involving PwPD, both with and without feelings of loneliness, was conducted to validate the number and duration of balance trials. Consistent with previous research on learning in PD, the learning process in this study was conducted over three days [41, 42]: (1) **Day 1** – Participants first completed two familiarization trials, followed by 15 balance trials organized into five blocks (Blocks 1–5) to enhance balance maintenance time and assess learning. (2) **Day 2 & Day 7** – Participants completed two familiarization trials and a single block of three trials to evaluate short-term and long-term memory, respectively (Fig. 1) at the same time of Day 1. To ensure consistency, a 60-s break was provided between individual trials, and a 120-s break was given between blocks. The task remained consistent; however, participants were instructed to increase the duration of balance maintenance time during performance. To minimize bias, reduce the impact of motor symptoms, and ensure the safe execution of balance tasks, all protocols and assessments were conducted in the ON state (i.e., one hour after taking dopaminergic medication) and administered by a blinded assessor.

We selected the one- and six-day intervals for retention testing based on prior PD studies demonstrating these time frames as adequate for assessing motor learning and retention [41, 42].

To minimize the effects of diurnal variation on performance, all assessments were conducted at the same time of day for each participant across all sessions.

Given the importance of task challenge in the learning process, participants completed the National Aeronautics and Space Administration Task Load Index (NASA-TLX) following each training session. This visual analog scale assesses subjective workload and task complexity in balance tasks [65]. The assessment evaluates six dimensions—mental demand, physical demand, temporal demand, performance, effort, and frustration—using a scale from 0 (not demanding) to 20 (very demanding).

Data processing

In this study, the average duration of balance maintenance time in each performance block (three trials) was calculated as balance performance. Subsequently, we evaluated balance learning parameters, including the learning rate and slope, as well as balance memory, encompassing both short-term and long-term memory.

The balance learning rate was determined by calculating the percentage change in balance performance from the first block to the fifth block on the first day using the following formula [66]:

$$\frac{(\text{block5day1} - \text{block1day1})}{\text{block1day1}} \times 100$$

Additionally, the learning slope was calculated by determining the steepness of the line fit from the first block to the fifth block on the first day ($\tan \theta$).

Short-term memory was assessed by calculating the percentage change in balance performance from the final block on the first day (block5day1) to the single block on the second day (block1day2) using the following formula:

$$\frac{(\text{block1day2} - \text{block5day1})}{\text{block5day1}} \times 100$$

Similarly, long-term memory was evaluated by calculating the percentage change in balance performance from the final block on the first day (block5day1) to the single block on the seventh day (block1day7) using the following formula:

$$\frac{(\text{block1day7} - \text{block5day1})}{\text{block5day1}} \times 100$$

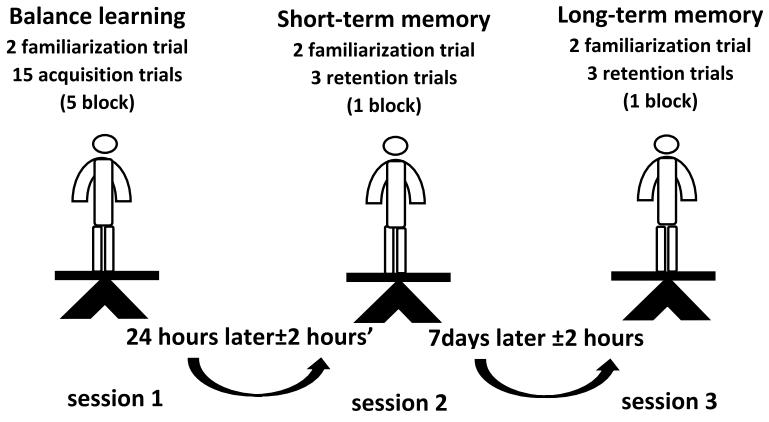

Fig. 1 Study protocol for balance learning (session 1) and memory (session 2 and 3)

Statistical analysis

The Shapiro–Wilk test was used to assess the normality of data distribution. For normally distributed continuous data, one-way analysis of variance (ANOVA) and independent t-tests were used for comparisons between three and two groups, respectively. In contrast, for continuous data that did not meet normality assumptions, the Kruskal–Wallis test and the Mann–Whitney U test were applied. Categorical variables were analyzed using the chi-square test.

Due to the non-normal distribution of balance performance, data from the first-day blocks (from block1day1 to block5day1) were log-transformed. Subsequently, balance performance on the first day was analyzed using mixed ANOVA, with time (from block 1 to block 5) as a within-group variable and group (loneliness- positive, loneliness- negative, and control) as a between-group variable.

One-way ANOVA was used to compare groups in terms of learning rate, learning slope on the first day, and long-term memory due to the normal distribution of data.

For post hoc analysis, Tukey's multiple comparisons test was applied in both one-way and mixed ANOVA tests. The effect size was calculated using partial eta squared (η^2) and classified based on the following values [67]:

- Small: ($\eta.^2 > 0.01$)
- Medium: ($\eta.^2 \geq 0.06$)
- Large: ($\eta.^2 \geq 0.14$)

Additionally, due to the non-normal distribution of data, the Kruskal–Wallis test with Bonferroni adjustment was used for group comparisons regarding short-term memory.

We conducted Pearson or Spearman correlation analyses, depending on the data distribution, to examine relationships between various loneliness measures (SELSA, TILS, and DJG) and multiple variables, including sex, marital status, education level, Edinburgh Handedness, more affected side, H&Y stage, age, LED, disease duration, MoCA, HADS-A/D, miniBESTest, UPDRS, fall history, TMT-A/B, VAS-P, FSS, PDFS, BAI, STAI-Trait, BDI, FES-I, PSQI, sleep duration, PDQ-39, RSEI, MSPSS, learning rate, learning slope, and both short- and long-term memory. These analyses were performed for all participants collectively as well as within subgroups. Furthermore, any variables demonstrating significant correlations with loneliness measures were subsequently included in Spearman or Pearson correlation analyses (depending on the distribution of data) with learning parameters to provide a more comprehensive understanding of contributing factors for in-depth discussion. The power of correlations was categorized as weak, moderate, and strong, with corresponding values of 0.10–0.39, 0.40–0.69, and ≥ 0.70, respectively [68].

The statistical significance level was set at $P \leq 0.05$.

Results

Demographic information and clinical characteristics of patients

The mean (± standard deviation) of demographic and descriptive variables is summarized in Table 1. The results indicated only significant differences in the Mini-BESTest and loneliness-related questionnaires—including the DjG, the TILS, and the total and subscale scores of SELSA-PD—between the loneliness-positive group and the loneliness-negative and control groups. Additionally, a significant difference was observed in the Mini-BESTest between the loneliness-positive and -negative groups. Significant correlations between the Mini-BESTest and loneliness-related questionnaires—including the DJG, TILS, and total and subscale scores of the SELSA-PD—were also observed in both the PwPD and control groups.

Balance performance

The mean and standard error of the mean for balance performance times (in seconds) across different balance blocks over three days for the control, loneliness-negative, and loneliness-positive groups are presented in Fig. 2. Figure 2 illustrates the comparison of balance performance times between groups, as well as between blocks within each group, across the three-day period.

The Mixed ANOVA analysis revealed significant main effects for group ($F_{(2,57)} = 12.73$, $p = 0.00$, $\eta^2 = 0.31$), time ($F_{(4,228)} = 40.22$, $p = 0.00$, $\eta^2 = 0.41$), and the group × time interaction ($F_{(8,228)} = 10.43$, $p = 0.00$, $\eta^2 = 0.27$) on balance maintenance time on the first day.

Multiple comparisons showed no significant difference in initial balance performance time between groups: $p = 0.76$ for healthy controls versus loneliness-negative, $p = 0.38$ for healthy controls versus loneliness-positive, and $p = 1.00$ for loneliness-negative versus loneliness-positive. For blocks 2 to 5, the p-values comparing healthy controls with loneliness-negative were 0.02, 0.01, 0.03, and 0.00, respectively; for healthy controls versus loneliness-positive, all p-values were 0.00. Comparisons between loneliness-negative and loneliness-positive yielded p-values of 0.64, 0.24, 0.25, and 0.04 across the blocks.

Pairwise comparisons for each group on the first day revealed that the loneliness-positive group showed no significant improvement in balance performance time ($p = 1.00$). In contrast, the loneliness-negative group demonstrated significant improvements, especially in early blocks (block1 vs. block 3: $p = 0.001$; block 1 vs. block 4: $p = 0.001$; block 1 vs. block 5: $p < 0.001$; block 2 vs. block

Table 1 Demographic and descriptive data for the control group ($n=20$) and Parkinson's disease patients without loneliness ($n=20$) and with loneliness ($n=20$)

Variables	Frequency (percent)/Mean (SD)				Significant level for comparing between control, loneliness negative and positive	Significant level for comparing between control and patients with Parkinson
	Control	Loneliness-negative	Loneliness-positive	Patients with Parkinson with and without loneliness		
Sex,: male/female (number)	13/7	13/7	13/7	26/14	-	1.00
Marital status: married/single (number)	15 (75%)/5 (25%)	16 (80%)/4 (20%)	18 (90%)/2 (10%)	34 (85%)/6 (15%)	0.46	0.35
Educational level: under diploma/ above diploma (number)	12 (60%)/8 (40%)	8 (40%)/12 (60%)	14 (70%)/6 (30%)	22 (55%)/18 (45%)	0.19	0.71
Edinburg Handedness inventory: right/ left/ two sides of power (number)	18 (90%)/1 (5%)/1 (5%)	19 (95%)/1 (5%)/0 (0%)	16 (80%)/2 (10%)/2 (10%)	35 (87.5%)/3 (7.5%)/2 (5%)	0.60	0.66
More affected side: right/left (number)	-	12 (60%)/8 (40%)	10 (50%)/10 (50%)	22 (55%)/18 (45%)	0.53	-
H&Y: 1/2/3/4/5 (number)	-	1 (5%)/12 (60%)/7 (35%)/0 (0%)/0 (0%)	0 (0%)/13 (65%)/7 (35%)/0 (0%)/0 (0%)	1 (2.5%)/25 (62.5%)/14 (35%)/0 (0%)/0 (0%)	0.60	-
Age (years)	69.35 (6.14)	71.88 (5.50)	70.35 (5.32)	71.11 (5.40)	-	0.25
BMI (kg/m^2)	24.88 (1.81)	24.05 (2.95)	24.81 (2.88)	24.43 (2.90)	-	0.47
LED (milligram)	-	784.40 (412.58)	1045.60 (574.43)	915.00 (511.06)	0.14	-
Disease duration (years)	-	6.70 (2.85)	8.10 (2.79)	7.40 (2.87)	0.13	-
MoCA (score)	26.65 (1.73)	26.60 (1.50)	25.70 (1.84)	26.15 (1.72)	0.11	0.28
HADS-A (score)	4.85 (1.79)	4.90 (2.36)	5.90 (1.65)	5.40 (2.07)	0.12	0.14
HADS-D (score)	4.80 (2.09)	4.85 (1.95)	5.85 (1.08)	5.35 (1.64)	0.24	0.37
Mini-Best test (score)	27.50 (0.89)	26.65 (1.14)*	25.20 (1.28)$^{+,*}$	25.93 (1.40)	**0.00**	**0.00**
UPDRS-ON phase (score)	-	25.15 (8.23)	26.20 (7.98)	25.68 (8.02)	0.68	-
Fall history during recent year (number)	-	1.25 (1.97)	1.70 (1.81)	1.48 (1.88)	0.38	-
TMT-part A (second)	45.29 (13.51)	48.20 (12.80)	50.88 (14.97)	49.54 (13.81)	0.24	0.11
TMT-part A (error number)	0.00 (0.00)	0.20 (0.70)	0.30 (0.73)	0.25 (0.71)	0.12	0.07
TMT-part B (second)	147.09 (51.88)	157.66 (54.01)	182.68 (68.98)	170.17 (62.45)	0.15	0.12
TMT-part B (error number)	2.10 (2.17)	1.60 (1.98)	2.35 (2.06)	1.98 (2.03)	0.43	0.69
VAS-pain (score)	3.15 (3.54)	4.70 (2.20)	3.23 (3.41)	3.96 (2.93)	0.13	0.29
FSS (score)	32.20 (2.63)	35.25 (9.44)	36.45 (5.56)	35.85 (7.67)	0.12	0.06
PDFS (score)	-	42.35 (12.30)	48.35 (12.86)	45.35 (12.79)	0.14	-
BAI (score)	12.20 (5.41)	17.25 (13.07)	18.10 (8.93)	17.68 (11.06)	0.18	0.09
STAI-state section (score)	39.05 (7.26)	40.30 (9.81)	45.10 (10.99)	42.70 (10.57)	0.12	0.13

Table 1 (continued)

Variables	Frequency (percent)/Mean (SD)				Significant level for comparing between control, loneliness negative and positive	Significant level for comparing between control and patients with Parkinson
	Control	Loneliness-negative	Loneliness-positive	Patients with Parkinson with and without loneliness		
STAI -trait section (score)	41.15 (8.66)	44.05 (7.34)	47.00 (9.25)	45.53 (8.37)	0.13	0.11
BDI (score)	16.85 (8.01)	16.10 (8.97)	20.45 (10.09)	18.28 (9.68)	0.28	0.48
FESI (score)	-	20.00 (4.92)	21.10 (4.44)	20.55 (4.66)	0.12	-
PSQI (score)	6.75 (2.36)	8.15 (4.31)	9.20 (4.41)	8.68 (4.33)	0.14	0.07
Hours of sleep after training and before retention (hour)	6.65 (1.27)	5.95 (1.70)	6.25 (1.59)	6.10 (1.63)	0.37	0.18
PDQ-39 (score)	-	27.82 (16.81)	34.98 (10.92)	31.40 (14.46)	0.12	-
DjG (score)	1.50 (0.69)	1.55 (0.51)	6.55 (2.80)$^{+,*}$	4.05 (3.22)	**0.00**	**0.01**
TILS (score)	3.65 (0.49)	4.05 (1.23)	6.05 (1.67)$^{+,*}$	5.05 (1.77)	**0.00**	**0.01**
SELSA-PD version (romantic section) (score)	8.05 (1.57)	8.15 (1.23)	16.40 (5.36)$^{+,*}$	12.28 (5.67)	**0.00**	**0.00**
SELSA-PD version (family section) (score)	4.55 (0.51)	4.75 (0.44)	12.50 (4.98)$^{+,*}$	8.63 (5.25)	**0.00**	**0.00**
SELSA-PD version (emotional section) (score)	12.60 (1.64)	12.90 (1.41)	28.90 (8.77)$^{+,*}$	20.90 (10.20)	**0.00**	**0.00**
SELSA-PD version (social section) (score)	8.00 (1.08)	7.70 (1.42)	15.55 (4.90)$^{+,*}$	11.63 (5.34)	**0.00**	**0.00**
SELSA-PD version (total) (score)	20.60 (2.21)	20.60 (2.19)	44.45 (10.66)$^{+,*}$	32.53 (14.27)	**0.00**	**0.00**
RSI (score)	30.05(2.56)	32.50 (13.89)	29.40 (4.82)	30.95 (10.38)	0.93	0.83
MSPSS (score)	67.05 (6.35)	68.90 (6.91)	62.95 (12.47)	65.93 (10.40)	0.11	0.61

H&Y Hoehn and Yahr, *BMI* Body Mass Index, *LED* Levodopa Equivalent Dose, *MoCA* Montrealcognitive assessment battery, *HADS-A* Hospital Anxiety Depression Scale-anxiety subscale, *HADS-D* Hospital Anxiety Depression Scale-depression subscale, *Mini-Best test* Mini Balance Evaluation Systems Test, *UPDRS-ON phase* Unified Parkinson's Disease Rating Scale-ONphase, *TMT* Trial Making Test, *VAS-pain* Visual Analog Scale for pain, *FSS* Fatigue Severity Scale, *PDFS* Parkinson's disease fatigue scale, *BAI* Beck Anxiety Inventory, *STAI* The state-traitanxiety inventory, *BDI* Beck Depression Inventory, *FESI* Fall Efficacy Scale-International, *PSQI* Pittsburgh Sleep Quality Index, *PDQ-39* 39-items Parkinson's Disease Quality of lifequestionnaire, *DjG* de Jong-Gierveld loneliness scale, *TILS* Three-Item Loneliness Scale, *SELSA-PD version* Social and Emotional Loneliness Scale for Adult-Parkinson's Disease version, *RSI* Rosenberg self-esteem inventory, *MSPSS* Multidimensional scale of perceived social support

$^{*}P < 0.05$ compared both the loneliness-positive and loneliness-negative groups with the controlgroup

$^{+}P < 0.05$ compared patients with loneliness with patients without it

5: $p = 0.014$). The control group exhibited continuous improvement throughout the first day's blocks, with significant differences across most comparisons ($p = 0.00$), except for block 2 vs. block 3 ($p = 0.21$), block 2 vs. block 4 ($p = 1.00$), and block 3 vs. block 4 ($p = 1.00$) (Fig. 2).

The Cohen's d values for group comparisons across various balance performance blocks in different groups are as follows:

Control Group:
- block1 vs block2: Cohen's d = -0.773 (moderate effect).
- block1 vs block3: Cohen's d = -1.128 (large effect).
- block1 vs block4: Cohen's d = -0.919 (large effect).
- block1 vs block5: Cohen's d = -1.944 (large effect).
- block2 vs block3: Cohen's d = -0.356 (small effect).
- block2 vs block4: Cohen's d = -0.232 (small effect).
- block2 vs block5: Cohen's d = -1.078 (large effect).
- block3 vs block4: Cohen's d = 0.080 (negligible effect).
- block3 vs block5: Cohen's d = -0.741 (moderate effect).
- block4 vs block5: Cohen's d = -0.735 (moderate effect).

Without Loneliness Group:
- block1 vs block2: Cohen's d = -0.396 (small effect).
- block1 vs block3: Cohen's d = -0.677 (moderate effect).
- block1 vs block4: Cohen's d = -0.672 (moderate effect).
- block1 vs block5: Cohen's d = -0.811 (large effect).
- block2 vs block3: Cohen's d = -0.284 (small effect).
- block2 vs block4: Cohen's d = -0.274 (small effect).

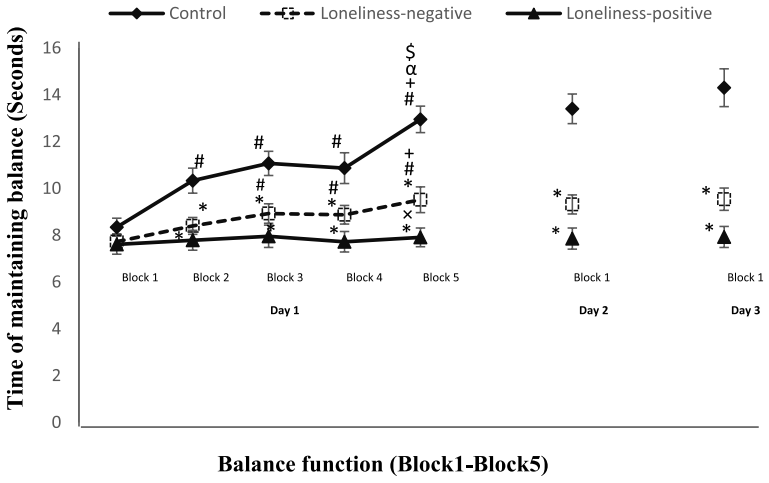

Fig. 2 Mean balance performance times with standard error of the mean (SEM) across various balance blocks over a three-day period for the control, loneliness-negative, and loneliness-positive groups. *: $P \leq 0.05$ – Comparison of balance performance time across different blocks between the control, loneliness-negative, and loneliness-positive groups. ×: $P \leq 0.05$ – Comparison of balance performance time across different blocks between the loneliness-negative, and loneliness-positive groups. #: $P \leq 0.05$ – Comparison of Block 1, Day 1 with other balance performance time blocks in all three groups. +: $P \leq 0.05$ – Comparison of Block 2, Day 1 with other balance performance time blocks in all three groups. α: $P \leq 0.05$ – Comparison of Block 3, Day 1 with other balance performance time blocks in all three groups. $: $P \leq 0.05$ – Comparison of Block 4, Day 1 with other balance performance time blocks in all three groups

- block2 vs block5: Cohen's d = -0.471 (small effect).
- block3 vs block4: Cohen's d = 0.013 (negligible effect).
- block3 vs block5: Cohen's d = -0.217 (small effect).
- block4 vs block5: Cohen's d = -0.231 (small effect).

With Loneliness Group:

- block1 vs block2: Cohen's d = -0.084 (negligible effect).
- block1 vs block3: Cohen's d = -0.144 (negligible effect).
- block1 vs block4: Cohen's d = -0.004 (negligible effect).
- block1 vs block5: Cohen's d = -0.155 (negligible effect).
- block2 vs block3: Cohen's d = -0.062 (negligible effect).
- block2 vs block4: Cohen's d = 0.080 (negligible effect).
- block2 vs block5: Cohen's d = -0.068 (negligible effect).
- block3 vs block4: Cohen's d = 0.141 (negligible effect).
- block3 vs block5: Cohen's d = -0.001 (negligible effect).
- block4 vs block5: Cohen's d = -0.152 (negligible effect).

Subjective workload and task complexity

The total scores of NASA-TLX index and its subcomponents are presented in Table 2. The results indicate that individuals in the loneliness-positive group experienced a higher temporal demand while maintaining balance on the stabilometer.

Balance learning

The mean ± standard deviation of the learning rate and learning slope in the loneliness-positive, loneliness-negative, and control groups are shown in Fig. 3.

The one-way ANOVA analysis for balance learning on the first day revealed a significant difference in both learning rate ($F_{(2,57)} = 37.60$, $p = 0.00$, $\eta^2 = 0.57$) and learning slope ($F_{(2,57)} = 34.92$, $p = 0.00$, $\eta^2 = 0.55$) among the three groups.

The Cohen's d values for group comparisons across various parameters are as follows:

- Rate of balance learning: Control vs. No Loneliness, 1.71; Control vs. Loneliness, 2.76; No Loneliness vs. Loneliness, 0.94
- Slope of balance learning: Control vs. No Loneliness, 1.52; Control vs. Loneliness, 2.74; No Loneliness vs. Loneliness, 1.22

Multiple comparisons indicated that balance learning ability (both learning rate and learning slope) was significantly weaker in the loneliness-positive group compared to both the loneliness-negative and the control groups ($p \leq 0.01$). Additionally, the loneliness-negative group also exhibited a significantly lower balance learning ability compared to the control group ($p = 0.00$) (Fig. 3).

Short-term and long-term memory

Figure 3 presents the mean ± standard deviation values for short-term and long-term memory in the loneliness-positive, loneliness-negative, and control groups.

The Kruskal–Wallis test and one-way ANOVA analysis revealed no significant differences between the groups in terms of short-term memory ($\chi^2 = 1.62$, $p = 0.48$) and long-term memory ($F_{(2,57)} = 2.59$, $p = 0.08$, $\eta^2 = 0.08$).

These results indicate that short-term and long-term memory remained stable across the groups, showing no significant changes.

The Cohen's d values for group comparisons across various parameters are as follows:

Table 2 The National Aeronautics and Space Administration-Task Load Index (NASA-TLX) characteristics over three days of learning for the control group ($n=20$), the loneliness-negative group ($n=20$), and the loneliness-positive group ($n=20$)

Balance learning stage	**First day**			
Groups	**Control**	**Loneliness-negative**	**loneliness-positive**	**Significant level**
Sections	**Mean ± SD**			
Raw Task Load Index (RTLX)	75.05 ± 15.08	77.05 ± 17.41	81.00 ± 13.87	0.47
Mental demand	15.20 ± 3.38	15.00 ± 4.41)	16.75 ± 3.06	0.36
Physical demand	15.30 ± 2.30	15.85 ± 3.27)	16.45 ± 2.68	0.32
Temporal demand	8.40 ± 6.46	12.85 ± 6.69*	13.70 ± 6.78*	**0.03**
Performance	12.90 ± 3.63	11.55 ± 3.35	10.40 ± 5.11	0.07
Effort	16.20 ± 1.74	15.40 ± 3.38	16.60 ± 3.33	0.37
Frustration	7.15 ± 6.15	6.65 ± 5.97	7.35 ± 6.64	0.93
Balance learning stage	**Second day**			
Groups	**Control**	**Loneliness-negative**	**loneliness-positive**	**Significant level**
Sections	**Mean ± SD**			
Raw Task Load Index (RTLX)	75.25 ± 11.30	77.05 ± 15.83	81.95 ± 13.89	0.29
Mental demand	15.60 ± 2.76	16.35 ± 3.38	16.85 ± 3.39	0.17
Physical demand	15.80 ± 2.76	16.40 ± 3.44	16.35 ± 2.76	0.69
Temporal demand	7.50 ± 6.19	11.60 ± 6.74	12.65 ± 6.06*	**0.03**
Performance	13.85 ± 4.98	12.40 ± 3.14	11.65 ± 5.73	0.25
Effort	16.70 ± 2.74	15.80 ± 3.16	16.80 ± 2.63	0.61
Frustration	5.80 ± 6.65)	5.15 ± 5.82	7.15 ± 7.22	0.72
Balance learning stage	**Seventh day**			
Groups	**Control**	**Loneliness-negative**	**loneliness-positive**	**Significant level**
Sections	**Mean ± SD**			
Raw Task Load Index (RTLX)	80.55 ± 11.13	80.80 ± 16.86	81.25 ± 18.29	0.99
Mental demand	16.65 ± 2.39	16.70 ± 3.40	16.60 ± 4.28	0.63
Physical demand	16.15 ± 2.37	16.80 ± 3.35	16.25 ± 4.44	0.36
Temporal demand	9.80 ± 6.18	10.90 ± 6.99	14.35 ± 6.16*,+	**0.02**
Performance	14.30 ± 3.84	13.85 ± 3.87	11.85 ± 5.05	0.10
Effort	17.05 ± 1.43	15.70 ± 4.68	17.30 ± 2.87	0.55
Frustration	6.10 ± 7.13	7.10 ± 6.61	7.40 ± 6.67	0.86

*$P < 0.05$ compared both the loneliness-positive and loneliness-negative groups with the controlgroup

+$P < 0.05$ compared the loneliness-positive group with the loneliness-negative group

- Short-term memory: Control vs. No Loneliness, 1.16; Control vs. Loneliness, 1.82; No Loneliness vs. Loneliness, 0.77
- Long-term memory: Control vs. No Loneliness, 0.63; Control vs. Loneliness, 1.49; No Loneliness vs. Loneliness, 0.87

According to Cohen's guidelines, values of 0.2, 0.5, and 0.8 correspond to small, medium, and large effect sizes, respectively, indicating that most observed effects are large or very large.

Confounding effects of depression and anxiety on the relationship between loneliness and learning parameters

To minimize the confounding effects of anxiety and depression, we excluded patients with severe symptoms using the HADS cutoff scores and incorporated additional assessments with BDI (cutoff 14/15) [69] and BAI (cutoff 12/13) [70]. We then classified patients into groups with and without depression and anxiety, respectively, to evaluate their impact on the relationship between loneliness and balance maintenance time and learning.

The mean ± standard deviation of anxiety and depression severity, based on the BAI cut-off score (12/13) BDI cut-off score (14/15), are reported in the Table 3.

We performed mixed ANOVA tests to assess the covariate effects of anxiety and depression on balance maintenance time across trials. Mixed ANOVA controlling for anxiety revealed significant main effects of group ($F(2,56) = 12.44$, $p < 0.001$, $\eta^2 = 0.31$), time ($F(4,224) = 14.09$, $p < 0.001$, $\eta^2 = 0.20$), and group × time interaction ($F(8,224) = 10.69$, $p < 0.001$, $\eta^2 = 0.28$), with no significant main effect of anxiety ($F(1,56) = 0.09$, $p = 0.77$, $\eta^2 = 0.002$) or anxiety × time interaction ($F(4,224) = 1.64$, $p = 0.17$, $\eta^2 = 0.03$). Controlling for depression yielded similar results: significant main effects of group ($F(2,56) = 12.11$, $p < 0.001$, $\eta^2 = 0.30$), time ($F(4,224) = 15.31$, $p < 0.001$, $\eta^2 = 0.22$), and group × time interaction ($F(8,224) = 10.59$, $p < 0.001$, $\eta^2 = 0.27$), but

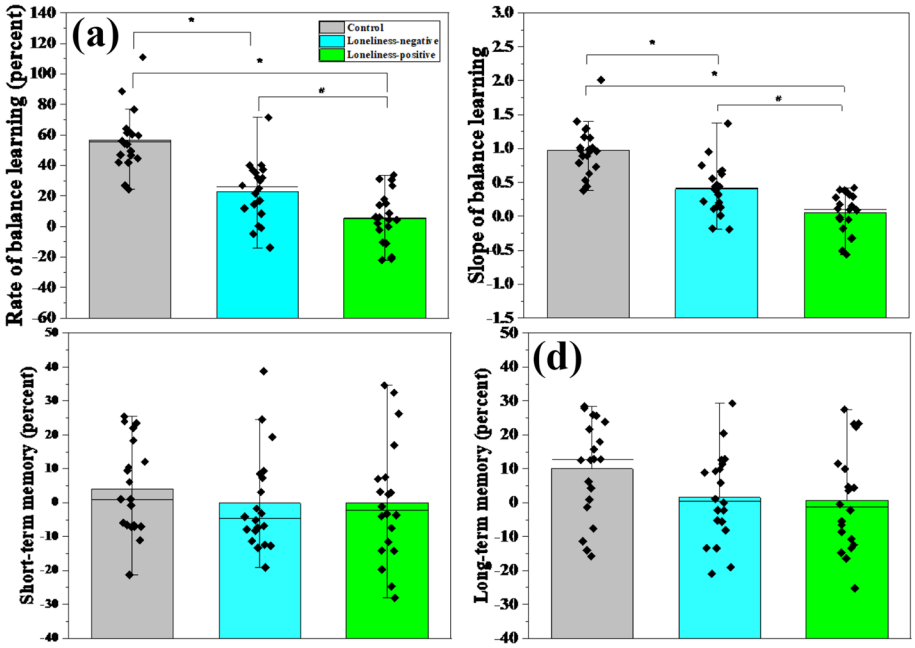

Fig. 3 Bar plot showing group means and standard deviations, with superimposed individual data points to demonstrate data variability of the (**a**) learning rate, (**b**) learning slope, (**c**) short-term memory, and (**d**) long-term memory across three groups: Control ($n = 20$), Loneliness-negative ($n = 20$), and Loneliness-positive ($n = 20$). *: $P \leq 0.05$– significant differences in learning parameters (learning rate, learning slope, short-term memory, long-term memory) between the Control group and the other groups (Loneliness-positive and Loneliness-negative). #: $P \leq 0.05$– significant differences in learning parameters (learning rate, learning slope, short-term memory, long-term memory) between the Loneliness-negative and Loneliness-positive groups

Table 3 The mean ± standard deviation of anxiety and depression severity, based on the Beck Anxiety Inventory (BAI) cut-off score (12/13) and Beck Depression Inventory (BDI) cut-off score (14/15)

Group	With anxiety	Without anxiety	With depression	Without loneliness
Control	16.10 ± 5.13	8.30 ± 1.25	23.09 ± 4.25	9.22 ± 3.27
Without-loneliness	26.25 ± 8.43	3.75 ± 2.12	23.00 ± 4.43	7.67 ± 4.61
With-loneliness	22.79 ± 5.75	7.17 ± 3.49	25.71 ± 6.66	8.17 ± 3.60

no significant depression main effect ($F(1,56) = 0.33$, $p = 0.57$, $\eta^2 = 0.01$) or interaction ($F(4,224) = 1.70$, $p = 0.15$, $\eta^2 = 0.03$). These findings indicate significant differences in balance maintenance time among loneliness-positive, loneliness-negative, and healthy controls, independent of anxiety or depression.

Two-way ANOVA examined group (loneliness-positive, loneliness-negative, healthy controls) and psychological status (with/without depression or anxiety) effects on learning rate, learning slope, and memory parameters.

For depression, learning rate showed a significant group effect ($F(2,54) = 33.76$, $p < 0.001$, $\eta^2 = 0.56$) but no main effect (F (1, 54) = 1.00 $p = 0.32$, $\eta^2 = 0.02$) or interaction (F (2, 54) = 0.20, $p = 0.82$, $\eta^2 = 0.01$) with depression status. Post hoc tests revealed significantly lower learning rates in loneliness-positive individuals versus loneliness-negative ($p = 0.02$) and controls ($p < 0.001$), regardless of depression. Learning slope mirrored these results, with a significant group effect ($F(2,54) = 31.52$, $p < 0.001$, $\eta^2 = 0.54$), no depression effect (F (1, 54) = 0.03 $p = 0.87$, $\eta^2 = 0.00$) or interaction (F (2, 54) = 0.72, $p = 0.49$, $\eta^2 = 0.03$), and lower slopes in loneliness-positive participants versus loneliness-negative ($p = 0.01$) and controls ($p < 0.001$), regardless of depression. No significant effects of group (F (2, 54) = 0.48, $p = 0.62$, $\eta^2 = 0.02$) and F (2, 54) = 2.27, $p = 0.11$, $\eta^2 = 0.08$), depression (F (1, 54) = 2.11 $p = 0.15$, $\eta^2 = 0.04$ and F (1, 54) = 0.19 $p = 0.66$, $\eta^2 = 0.004$), or their interaction (F (2, 54) = 1.36, $p = 0.27$, $\eta^2 = 0.05$) and F (2, 54) = 0.06, $p = 0.94$, $\eta^2 = 0.002$) were observed for short- and long-term memory, respectively.

For anxiety, significant group effects were observed for learning rate ($F(2,54) = 34.64$, $p < 0.001$, $\eta^2 = 0.56$) and learning slope ($F(2,54) = 35.67$, $p < 0.001$, $\eta^2 = 0.57$). However, no significant main effects ($F(1,54) = 1.15$, $p = 0.29$, $\eta^2 = 0.02$; $F(1,54) = 1.14$, $p = 0.29$, $\eta^2 = 0.02$) or interactions ($F(2,54) = 0.67$, $p = 0.52$, $\eta^2 = 0.02$; $F(2,54) = 1.88$, $p = 0.16$, $\eta^2 = 0.07$) involving anxiety status were observed for these measures. Post hoc comparisons revealed that loneliness-positive individuals exhibited significantly lower learning rates and slopes, independent of anxiety status, compared to both loneliness-negative patients ($p = 0.02$ and $p = 0.01$, respectively) and healthy controls ($p < 0.001$ for both).

No significant differences were found for short-term memory, with no main effect of group ($F(2,54) = 0.32$, $p = 0.73$, $\eta^2 = 0.01$), anxiety status ($F(1,54) = 2.68$, $p = 0.11$,

$\eta^2 = 0.05$), or their interaction ($F(2,54) = 0.44$, $p = 0.64$, $\eta^2 = 0.02$).

Notably, anxiety had a significant main effect on long-term memory ($F(1,54) = 6.02$, $p = 0.02$, $\eta^2 = 0.10$), with participants without anxiety demonstrating better performance across groups. The mean (± SD) long-term memory scores were 9.90 (± 12.89) for participants without anxiety and 0.20 (± 14.50) for participants with anxiety (see Fig. 4). There was no significant main effect of group ($F(2,54) = 1.67$, $p = 0.20$, $\eta^2 = 0.06$) nor a significant group × anxiety interaction ($F(2,54) = 0.89$, $p = 0.42$, $\eta^2 = 0.03$).

Given that loneliness-positive patients showed minimal learning capacity on day one, this anxiety-related effect on long-term memory does not critically influence our main findings.

Overall, anxiety and depression did not significantly influence learning parameters, supporting loneliness as the primary contributor to reduced learning ability. The absence of anxiety and depression effects may reflect exclusion of severe cases and limited sample size, warranting further investigation.

Results of correlation analyses between loneliness measures and various variables

The results of correlation analyses between loneliness measures and multiple variables are presented for all participants, healthy controls, loneliness-negative, and loneliness-positive groups in Tables 4, 5, 6, and 7, respectively. Additionally, Table 8 presents the correlations between learning parameters and demographic variables that showed at least one significant association with a loneliness measure.

The only significant correlations were observed between the Mini-BESTest, FES-I, TMT-Part B, and BAI, each of which correlated with both loneliness measures and learning parameters.

Discussion

Loneliness is highly prevalent among PwPD, ranging from 24.1% to 53.8% [14]. Beyond maladaptive behavioral patterns, loneliness creates complex interactions between the body and brain, increasing susceptibility to both mental and physical health issues, particularly balance impairments in PwPD [71].

In this context, the present pioneering study examines the impact of loneliness on balance learning, a critical element of balance rehabilitation in PwPD, as it enhances postural control through repeated, reinforced motor practice [16]. Although, in theory, loneliness-positive patients are expected to exhibit poorer balance maintenance time than loneliness-negative counterparts, our findings did not reveal a significant difference in initial balance maintenance time, as measured using a stabilometer. However, the key finding of this study was the potential negative impact of loneliness on dynamic balance learning, highlighting the need to address loneliness in balance rehabilitation, which requires further investigation. Given the overlap of brain regions involved in both memory and loneliness, as reported in previous study [72], it is plausible that loneliness may also impair memory. However, in our study, loneliness-positive patients showed no learning potential; thus, their short-term and long-term memory remained unchanged from baseline. In contrast, loneliness-negative patients and healthy controls demonstrated improved balance learning ability, which was maintained over time, indicating stable short-term and long-term memory in these groups.

Previous studies have shown that loneliness-positive patients exhibit greater balance impairments [16], as reflected in the miniBESTest results in our study.

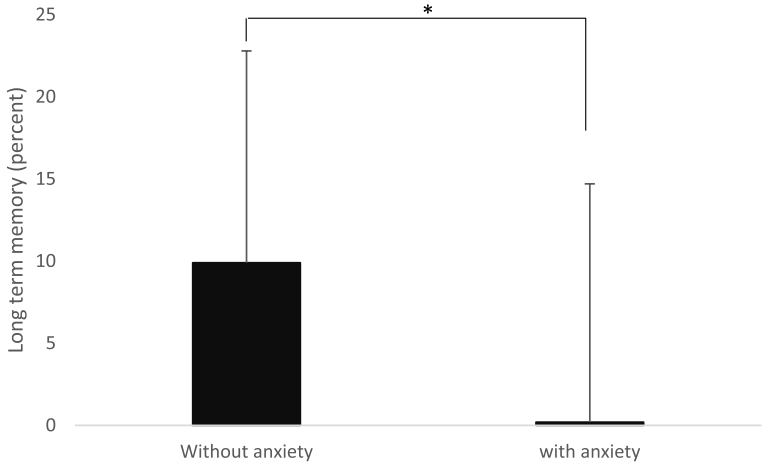

Fig. 4 Comparison of the mean percentage and standard deviation of long-term memory in patients with Parkinson's disease with and without anxiety. * indicates a significant difference between the groups ($p \leq 0.05$)

Table 4 Spearman correlation analysis between loneliness measurements and different clinical variables for all participants ($n = 60$)

Clinical variables		Sex	Marital status	Educational level	EDINBORG	More affected side	H&Y	age	BMI	LED	Disease duration	MOCA	HADS-A	HADS-D
SELSA TOTAL	ρ	-0.16	-0.26*	-0.17	0.13	0.13	0.11	-0.04	0.09	0.06	0.26	-0.30*	0.38**	0.37**
	Sig levels	0.21	0.05	0.21	0.43	0.43	0.51	0.74	0.52	0.73	0.11	**0.02**	**0.00**	**0.004**
TILS	ρ	-0.11	-0.26*	-0.05	0.21	0.21	-0.18	-0.15	0.11	0.04	0.05	-0.20	0.40**	0.23
	Sig levels	0.40	**0.05**	0.69	0.20	0.20	0.28	0.26	0.42	0.81	0.75	0.14	**0.00**	0.08
DjG	ρ	0.00	**-0.04**	-0.20	0.07	0.07	-0.08	0.04	0.09	0.05	0.01	-0.25	0.44**	0.42**
	Sig levels	0.98	0.79	0.13	0.67	0.67	0.64	0.77	0.51	0.76	0.97	0.06	**0.00**	**0.00**

Clinical variables		Mini-Best test	UPDRS-ON phase	Fall history	TMT-part A	TMTA-error number	TMT-part B	TMTB-error number	VAS-pain	FSS	PDFS	BAI	STAI-state part	TRAIT-trait part
SELSA TOTAL	ρ	-0.54**	0.06	0.24	0.12	0.07	0.07	0.01	-0.09	0.21	0.28	0.31*	0.35**	0.39**
	Sig levels	**0.00**	0.73	0.06	0.37	0.60	0.62	0.96	0.50	0.10	0.08	**0.02**	**0.01**	**0.002**
TILS	ρ	-0.33*	0.05	0.20	-0.03	0.09	0.09	0.12	-0.08	0.32*	0.06	0.25	0.39**	0.34**
	Sig levels	**0.01**	0.77	0.12	0.81	0.51	0.50	0.38	0.56	**0.01**	0.74	0.06	**0.002**	**0.01**
DjG	ρ	-0.43**	0.11	0.14	0.26*	0.12	0.23	0.22	-0.07	0.32*	0.19	0.39**	0.34**	0.42**
	Sig levels	**0.00**	0.52	0.29	**0.04**	0.35	0.07	0.09	0.60	**0.01**	0.25	**0.002**	**0.01**	**0.001**

Clinical variables		BDI	FESI	PSQI	The number of sleep hours	PDQ-39	RSI	MSPSS	NASA-TLX	Learning rate	Learning slope	Short-term memory	Long-term memory
SELSA TOTAL	ρ	0.31*	0.51**	0.23	-0.12	0.34*	-0.11	-0.15	0.25	-0.49**	-0.55**	-0.11	-0.18
	Sig levels	**0.02**	**0.00**	0.08	0.35	0.03	0.41	0.24	0.05	**0.00**	**0.00**	0.39	0.18
TILS	ρ	0.45**	0.32*	0.19	-0.09	0.21	-0.14	-0.24	0.19	-0.24	-0.33*	0.01	0.08
	Sig levels	**0.000**	**0.01**	0.15	0.49	0.19	0.30	0.07	0.16	0.07	**0.01**	0.97	0.54
DjG	ρ	0.40**	0.47**	0.31*	-0.06	0.34*	-0.16	-0.36**	-0.03	-0.31*	-0.38**	-0.10	-0.17
	Sig levels	**0.001**	**0.000**	**0.02**	0.64	**0.03**	0.23	**0.00**	0.83	**0.02**	**0.003**	0.47	0.19

SELSA-PDversion Social and Emotional Loneliness Scale for Adult-Parkinson's Disease version, *TILS* Three-Item Loneliness Scale, *DjG* De Jong-Gierveld loneliness scale, *H&Y* Hoehn and Yahr, *BMI* Body Mass Index, *LED* Levodopa Equivalent Dose, *MoCA* Montreal cognitive assessment battery, *HADS-A* Hospital Anxiety Depression Scale-anxiety subscale, *HADS-D* Hospital Anxiety Depression Scale-depression subscale, *Mini-Best test* Mini Balance Evaluation Systems Test, *UPDRS-ONphase* Unified Parkinson's Disease Rating Scale-ON phase, *TMT* Trial Making Test, *VAS-pain* Visual Analog Scale for pain, *FSS* Fatigue Severity Scale, *PDFS* Parkinson's disease fatigue scale, *BAI* Beck Anxiety Inventory, *STAI* The state-trait anxiety inventory, *BDI* Beck Depression Inventory, *FESI* Fall Efficacy Scale-International, *PSQI* Pittsburgh Sleep Quality Index, *PDQ-39* 39-items Parkinson's Disease Quality of life questionnaire, *RSI* Rosenberg self-esteem inventory, *MSPSS* Multidimensional scale of perceived social support, *NASA-TLX* National Aeronautics and Space Administration-Task Load Index

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

Table 5 Spearman correlation analysis between loneliness measurements and different clinical variables for healthy participants ($n = 20$)

Clinical variables		Sex	Marital status	Educational level	EDINBORG	More affected side	H&Y	age	BMI	LED	Disease duration	MOCA	HADS-A	HADS-D
SELSA TOTAL	ρ	-0.44	-0.28	0.12	0.05	-	-	-0.15	0.09	-	-	-0.37	0.40	0.25
	Sig levels	0.05	0.24	0.62	0.83	-	-	0.53	0.71	-	-	0.11	0.08	0.29
TILS	ρ	-0.34	-0.55*	0.45*	0.24	-	-	-0.29	0.34	-	-	-0.18	0.50*	0.08
	Sig levels	0.14	0.01	0.04	0.30	-	-	0.22	0.15	-	-	0.46	0.03	0.75
DjG	ρ	0.02	-0.16	-0.27	-0.02	-	-	0.37	0.62**	-	-	-0.23	0.53*	0.48*
	Sig levels	0.93	0.50	0.26	0.94	-	-	0.11	0.00	-	-	0.33	0.02	0.03

Clinical variables		Mini-Best test	UPDRS-ON phase	Fall history	TMT-part A	TMTA-error number	TMT-part B	TMTB-error number	VAS-pain	FSS	PDFS	BAI	STAI-state part	TRAIT-trait part
SELSA TOTAL	ρ	-0.37	-	-	-0.02		-0.11	-0.14	0.06	0.03	-	0.59**	0.33	0.52*
	Sig levels	0.11	-	-	0.94		0.63	0.55	0.80	0.90	-	0.01	0.16	0.02
TILS	ρ	-0.18	-	-	-0.26		-0.14	-0.10	-0.14	0.16	-	0.53*	0.46*	0.65**
	Sig levels	0.44	-	-	0.26		0.57	0.69	0.55	0.49	-	0.02	0.04	0.002
DjG	ρ	-0.25	-	-	0.50*		0.68**	0.30	0.09	-0.21	-	0.57**	0.60**	0.50*
	Sig levels	0.28	-	-	0.02		0.001	0.20	0.72	0.37	-	0.01	0.01	0.02

Clinical variables		BDI	FESI	PSQI	The number of sleep hours	PDQ-39	RSI	MSPSS	NASA-TLX	Learning rate	Learning slope	Short-term memory	Long-term memory
SELSA TOTAL	ρ	0.49*	-	-0.13	-0.07	-	0.04	0.14	.44	0.09	-0.20	-0.21	0.11
	Sig levels	0.03	-	0.59	0.77	-	0.87	0.57	.05	0.72	0.39	0.38	0.64
TILS	ρ	0.73**	-	0.04	0.01	-	0.37	0.26	.08	0.37	-0.12	-0.26	0.26
	Sig levels	0.00	-	0.88	0.97	-	0.11	0.26	.73	0.11	0.62	0.26	0.26
DjG	ρ	0.49*	-	0.29	-0.05	-	0.24	-0.05	-.28	0.26	-0.18	-0.32	-0.46*
	Sig levels	0.03	-	0.21	0.85	-	0.31	0.84	.23	0.26	0.46	0.17	0.04

SELSA-PDversion Social and Emotional Loneliness Scale for Adult-Parkinson's Disease version, *TILS* Three-Item Loneliness Scale, *DjG* De Jong-Gierveld loneliness scale, *H&Y* Hoehn and Yahr, *BMI* Body Mass Index, *LED* Levodopa Equivalent Dose, *MoCA* Montreal cognitive assessment battery, *HADS-A* Hospital Anxiety Depression Scale-anxiety subscale, *HADS-D* Hospital Anxiety Depression Scale-depression subscale, *Mini-Best test* Mini Balance Evaluation Systems Test, *UPDRS-ONphase* Unified Parkinson's Disease Rating Scale-ON phase, *TMT* Trial Making Test, *VAS-pain* Visual Analog Scale for pain, *FSS* Fatigue Severity Scale, *PDFS* Parkinson's disease fatigue scale, *BAI* Beck Anxiety Inventory, *STAI* The state-trait anxiety inventory, *BDI* Beck Depression Inventory, *FESI* Fall Efficacy Scale-International, *PSQI* Pittsburgh Sleep Quality Index, *PDQ-39* 39-items Parkinson's Disease Quality of life questionnaire, *RSI* Rosenberg self-esteem inventory, *MSPSS* Multidimensional scale of perceived social support, *NASA-TLX* National Aeronautics and Space Administration-Task Load Index

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

Table 6 Spearman correlation analysis between loneliness measurements and different clinical variables for patients without loneliness ($n=20$)

Clinical variables		Sex	Marital status	Educational level	EDINBORG	More affected side	H&Y	age	BMI	LED	Disease duration	MOCA	HADS-A	HADS-D
SELSA TOTAL	ρ	-0.45*	-0.31	0.04	-0.02	0.19	-0.13	0.12	0.03	-0.34	0.06	-0.26	0.39	0.40
	Sig levels	0.05	0.19	0.88	0.93	0.42	0.59	0.63	0.90	0.14	0.79	0.27	0.09	0.08
TILS	ρ	-0.21	-0.34	0.24	0.32	0.33	-0.38	-0.36	0.15	-0.25	-0.16	-0.04	0.49*	0.34
	Sig levels	0.39	0.15	0.32	0.17	0.15	0.10	0.12	0.53	0.28	0.51	0.85	0.03	0.15
DjG	ρ	-0.39	0.20	-0.10	0.21	0.12	-0.22	0.19	-0.03	-0.17	-0.25	-0.41	0.25	0.21
	Sig levels	0.90	0.40	0.68	0.38	0.61	0.35	0.41	0.91	0.48	0.30	0.07	0.28	0.37

Clinical variables		Mini-Best test	UPDRS-ON phase	Fall history	TMT-part A	TMTA-error number	TMT-part B	TMTB-error number	VAS-pain	FSS	PDFS	BAI	STAI-state part	TRAIT-trait part
SELSA TOTAL	ρ	0.23	0.01	-0.38	0.08	-0.28	-0.31	-0.29	-0.04	-0.02	0.45*	0.29	0.44	0.28
	Sig levels	0.33	0.96	0.10	0.75	0.24	0.18	0.21	0.86	0.93	0.05	0.21	0.05	0.23
TILS	ρ	0.23	0.01	-0.02	-0.09	-0.10	0.22	0.20	0.01	0.35	0.12	0.19	0.15	0.26
	Sig levels	0.33	0.96	0.94	0.70	0.69	0.34	0.39	0.98	0.13	0.63	0.42	0.53	0.27
DjG	ρ	-0.01	-0.14	-0.05	0.44*	-0.02	0.22	0.06	0.02	0.45*	0.25	0.24	0.18	0.21
	Sig levels	0.97	0.56	0.84	0.05	0.94	0.36	0.81	0.94	0.05	0.30	0.30	0.44	0.38

Clinical variables		BDI	FESI	PSQI	The number of sleep hours	PDQ-39	RSI	MSPSS	NASA-TLX	Learning rate	Learning slope	Short-term memory	Long-term memory
SELSA TOTAL	ρ	0.06	0.19	0.21	-0.28	0.18	-0.24	0.04	0.24	-0.12	-0.03	0.08	-0.17
	Sig levels	0.80	0.43	0.36	0.23	0.46	0.31	0.87	0.30	0.61	0.91	0.73	0.47
TILS	ρ	0.35	-0.08	-0.18	0.18	0.03	-0.39	-0.34	0.37	0.31	0.29	0.21	0.08
	Sig levels	0.13	0.75	0.46	0.45	0.91	0.09	0.14	0.11	0.19	0.21	0.38	0.74
DjG	ρ	-0.02	0.21	-0.11	0.36	-0.21	-0.46*	-0.39	0.34	0.34	0.24	-0.13	0.04
	Sig levels	0.94	0.37	0.63	0.12	0.38	0.04	0.09	0.14	0.14	0.32	0.58	0.86

SELSA-PDversion Social and Emotional Loneliness Scale for Adult-Parkinson's Disease version, *TILS* Three-Item Loneliness Scale, *DjG* De Jong-Gierveld loneliness scale, *H&Y* Hoehn and Yahr, *BMI* Body Mass Index, *LED* Levodopa Equivalent Dose, *MoCA* Montreal cognitive assessment battery, *HADS-A* Hospital Anxiety Depression Scale-anxiety subscale, *HADS-D* Hospital Anxiety Depression Scale-depression subscale, *Mini-Best test* Mini Balance Evaluation Systems Test, *UPDRS-ONphase* Unified Parkinson's Disease Rating Scale-ON phase, *TMT* Trial Making Test, *VAS-pain* Visual Analog Scale for pain, *FSS* Fatigue Severity Scale, *PDFS* Parkinson's disease fatigue scale, *BAI* Beck Anxiety Inventory, *STAI* The state-trait anxiety inventory, *BDI* Beck Depression Inventory, *FESI* Fall Efficacy Scale-International, *PSQI* Pittsburgh Sleep Quality Index, *PDQ-39* 39-items Parkinson's Disease Quality of life questionnaire, *RSI* Rosenberg self-esteem inventory, *MSPSS* Multidimensional scale of perceived social support, *NASA-TLX* National Aeronautics and Space Administration-Task Load Index

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

Table 7 Spearman and Pearson correlation analysis between loneliness measurements and different clinical variables for patients with loneliness ($n = 20$)

Clinical variables		Sex	Marital status	Educational level	EDINBORG	More affected side	H&Y	age	BMI	LED	Disease duration	MOCA	HADS-A	HADS-D
SELSA TOTAL	ρ/r	0.34	0.04	-0.13	-0.02	-0.02	0.47*	-0.29	-0.09	-0.26	0.06	0.31	-0.06	0.26
	Sig levels	0.15	0.86	0.58	0.93	0.94	0.04	0.21	0.70	0.27	0.80	0.19	0.80	0.26
TILS	ρ/r	0.16	0.34	-0.15	0.13	0.07	-0.02	0.10	-0.06	-0.17	-0.22	-0.002	-0.004	-0.18
	Sig levels	0.51	0.14	0.52	0.58	0.77	0.94	0.68	0.81	0.49	0.36	0.99	0.99	0.44
DjG	ρ/r	0.08	0.44	0.00	-0.18	-0.26	-0.19	-0.19	-0.25	-0.20	-0.23	0.15	0.29	0.46*
	Sig levels	0.73	0.05	1.00	0.45	0.28	0.43	0.41	0.29	0.41	0.33	0.52	0.21	0.04

Clinical variables		Mini-Best test	UPDRS-ON phase	Fall history	TMT-part A	TMTA-error number	TMT-part B	TMTB-error number	VAS-pain	FSS	PDFS	BAI	STAI-state part	TRAIT-trait part
SELSA TOTAL	ρ/r	-0.31	0.13	0.20	-0.46*	-0.39	-0.26	0.06	-0.01	0.14	-0.07	0.11	0.07	-0.14
	Sig levels	0.18	0.60	0.41	0.04	0.09	0.27	0.79	0.98	0.55	0.77	0.65	0.77	0.57
TILS	ρ/r	-0.04	0.02	0.18	-0.25	0.06	-0.31	-0.02	-0.00	0.08	-0.16	0.08	0.18	0.05
	Sig levels	0.86	0.94	0.44	0.30	0.79	0.19	0.95	0.99	0.73	0.50	0.74	0.46	0.84
DjG	ρ/r	0.05	0.27	-0.22	-0.18	0.10	-0.31	0.09	0.18	0.16	0.03	0.58**	0.34	0.08
	Sig levels	0.84	0.24	0.35	0.45	0.66	0.18	0.71	0.45	0.50	0.92	0.01	0.14	0.73

Clinical variables		BDI	FESI	PSQI	The number of sleep hours	PDQ-39	RSI	MSPSS	NASA-TLX	Learning rate	Learning slope	Short-term memory	Long-term memory
SELSA TOTAL	ρ/r	0.18	0.45*	0.14	-0.01	0.11	-0.04	-0.07	-0.17	-0.12	-0.20	-0.20	-0.01
	Sig levels	0.46	0.05	0.57	0.98	0.64	0.88	0.79	0.49	0.63	0.41	0.41	0.96
TILS	ρ/r	0.28	0.08	0.22	-0.34	0.14	-0.08	0.01	-0.02	0.34	0.08	0.10	0.53*
	Sig levels	0.24	0.75	0.35	0.14	0.55	0.73	0.98	0.94	0.15	0.74	0.68	0.02
DjG	ρ/r	0.49*	0.52*	0.40	-0.35	0.45*	-0.26	-0.45*	-0.36	0.03	0.11	0.04	0.16
	Sig levels	0.03	0.02	0.08	0.13	0.05	0.28	0.05	0.12	0.89	0.64	0.87	0.49

SELSA-PDversion Social and Emotional Loneliness Scale for Adult-Parkinson's Disease version, *TILS* Three-Item Loneliness Scale, *DjG* De Jong-Gierveld loneliness scale, *H&Y* Hoehn and Yahr, *BMI* Body Mass Index, *LED* Levodopa Equivalent Dose, *MoCA* Montreal cognitive assessment battery, *HADS-A* Hospital Anxiety Depression Scale-anxiety subscale, *HADS-D* Hospital Anxiety Depression Scale-depression subscale, *Mini-Best test* Mini Balance Evaluation Systems Test, *UPDRS-ONphase* Unified Parkinson's Disease Rating Scale-ON phase, *TMT* Trial Making Test, *VAS-pain* Visual Analog Scale for pain, *FSS* Fatigue Severity Scale, *PDFS* Parkinson's disease fatigue scale, *BAI* Beck Anxiety Inventory, *STAI* The state-trait anxiety inventory, *BDI* Beck Depression Inventory, *FESI* Fall Efficacy Scale-International, *PSQI* Pittsburgh Sleep Quality Index, *PDQ-39* 39-items Parkinson's Disease Quality of life questionnaire, *RSI* Rosenberg self-esteem inventory, *MSPSS* Multidimensional scale of perceived social support, *NASA-TLX* National Aeronautics and Space Administration-Task Load Index

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

Table 8 The correlation between learning parameters and different variables in all participants ($n=60$)

Learning parameters		Marital status	HADS-A	HADS-D	Mini-Best test	FESI	TMT-part A	TMTA-error number	TMT-part B
Learning rate	ρ/r	0.20	-0.09	-0.19	0.64**	-0.64**	-0.12	-0.27*	-0.11
	Sig levels	0.12	0.50	0.16	**0.00**	**0.00**	0.35	**0.04**	0.39
	N	60	60	60	60	60	60	60	60
Learning slope	ρ/r	0.28*	-0.16	-0.22	0.69**	-.63**	-0.12	-0.29*	-0.14
	Sig levels	0.**03**	0.22	0.09	**0.00**	**0.00**	0.38	**0.03**	0.30
	N	60	60	60	60	60	60	60	60
Short Term-memory	ρ/r	-0.00	-0.17	0.02	0.13	-0.17	-0.12	-0.06	-0.27*
	Sig levels	0.99	0.21	0.86	0.32	0.20	0.38	0.66	0.04
	N	60	60	60	60	60	60	60	60
Long Term-memory	ρ/r	0.12	-0.23	-0.11	0.29*	-0.33*	-0.35**	-0.34**	-0.18
	Sig levels	0.38	0.07	0.39	**0.02**	**0.01**	**0.01**	**0.01**	0.18
	N	60	60	60	60	60	60	60	60

Learning parameters		TMTB-error number	FSS	BAI	STAI-state part	TRAIT-trait part	BDI	PDQ-39
Learning rate	ρ/r	-0.09	-0.18	-0.11	-0.07	-0.15	-.09	-.06
	Sig levels	0.52	0.16	0.41	0.61	0.25	.52	.72
	N	60	60	60	60	60	60	40
Learning slope	ρ/r	-0.10	-0.22	-0.07	-0.11	-0.24	-0.16	-0.02
	Sig levels	0.46	0.10	0.61	0.39	0.07	0.22	0.91
	N	60	60	60	60	60	60	40
Short Term-memory	ρ/r	0.02	-0.05	-0.30*	-0.16	-0.17	-0.10	-0.03
	Sig levels	0.87	0.70	**0.02**	0.23	0.20	0.44	0.84
	N	60	60	60	60	60	60	40
Long Term-memory	ρ/r	-0.14	-0.13	-0.42**	-0.17	-0.26*	-0.11	-0.08
	Sig levels	0.28	0.34	**0.001**	0.19	**0.05**	0.42	0.64
	N	60	60	60	60	60	60	40

HADS-A Hospital Anxiety Depression Scale-anxiety subscale, *HADS-D* Hospital AnxietyDepression Scale-depression subscale, *Mini-Best test* Mini Balance Evaluation Systems Test, *FESI* Fall Efficacy Scale-International, *TMT* Trial Making Test, *FSS* Fatigue Severity Scale, *BAI* Beck Anxiety Inventory, *STAI* The state-trait anxiety inventory, *BDI* Beck Depression Inventory, *PDQ-39* 39-items Parkinson's Disease Quality of lifequestionnaire

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

However, unlike previous research, we did not find a significant difference in initial balance assessments among the groups (loneliness-positive, loneliness-negative, and control) using the stabilometer. The Mini-BESTest is a comprehensive clinical tool designed to evaluate multiple dimensions of dynamic balance and postural control, including anticipatory, reactive, sensory orientation, and dynamic gait components. It challenges a wide range of balance mechanisms and functional tasks that PwPD frequently encounter in daily life. This broad scope allows the Mini-BESTest to detect subtle impairments in balance control that affect overall functional mobility.

In contrast, the stabilometer focuses on a specialized aspect of balance—the ability to perform controlled medio-lateral weight shifting under a relatively constrained and static environment. While important, this specific task may not fully capture the multifaceted postural control challenges measured by the Mini-BESTest. Additionally, the stabilometer setting is more controlled and less representative of real-world dynamic conditions, potentially limiting its sensitivity to detect differences in balance that are more evident during complex, functional tasks evaluated by the Mini-BESTest. This difference in the constructs assessed by these tools explains why a performance difference appears in the Mini-BESTest but not in the stabilometer. Thus, we recommend that future studies incorporate more complex protocols, such as dual-task balance tests, when examining balance maintenance time.

Notably, loneliness-positive patients demonstrated a reduced ability to improve their balance maintenance time during training compared to those without loneliness. This may be due to dysfunctions in the neural systems responsible for motor actions essential for balance execution and improvement [39].

The most significant finding of our study was the impairment in voluntary dynamic balance learning in loneliness-positive patients, compared to the loneliness-negative and control groups. Loneliness may affect balance learning by modulating neural, physiological, and dopaminergic mechanisms, which warrant further investigation.

Neural mechanisms

This impairment is likely associated with a reduction in gray matter volume in brain regions involved in learning and cognition [73] along with loneliness. According to the attachment internal working models, human relationships shape neural networks and models, influencing the mind beyond genetic factors throughout life [74]. These models can be dynamically reorganized based on new relational and attachment experiences [73, 75]. The absence of meaningful interpersonal relationships leads to feelings of loneliness in older age [76]. Moreover, individuals who report higher levels of loneliness are less likely to engage in an active lifestyle. Active lifestyle provides social and cognitive stimulation, both of which are crucial for successful brain and cognitive aging [77, 78]. In fact, based on the evolutionary theory of loneliness, prolonged loneliness can lead to neurological changes [79] that may result in damage to brain regions essential for motor learning. For example, higher loneliness scores may be associated with: smaller gray matter volume in the left cerebellum [80], reduced striatal activity [81], alterations in cortico-striatal connectivity [82], changes in frontal lobe volume and connectivity [30], reduced gray matter in the anterior hippocampus [80]—a region crucial for motor skill learning, particularly balance-related tasks [27, 83–85]. However, since brain imaging was not performed in our study, these interpretations should be made with caution.

Physiological mechanisms

Loneliness acts as a chronic stressor, elevating cortisol levels and promoting a pro-inflammatory state. Persistent cortisol elevation can impair hippocampal and prefrontal cortex function, both vital for motor learning and memory consolidation. Inflammation further disrupts synaptic plasticity, reducing the brain's capacity to adapt and retain new balance strategies [10, 86].

Dopaminergic mechanisms

Dopaminergic pathways, which are already compromised in PD, are further influenced by psychosocial factors such as loneliness. Loneliness has been shown to reduce dopaminergic neuron activity [87], a critical effect for balance learning since diminished dopaminergic signaling impairs the neuroplastic adaptations essential for skilled motor performance [88, 89]. This highlights dopamine's central role in fundamental learning mechanisms, including long-term potentiation (LTP) and long-term depression (LTD), which are vital for motor learning and retention [90].

Patients in the loneliness-negative group also exhibited a lower capacity for improving balance learning compared to the control group. As previously discussed, changes in gray matter volume in the hippocampus and cerebellum—regions that are typically preserved in PwPD [91]—are associated with dynamic balance learning [27]. In the early phases of motor learning, these regions partially compensate for striatal dysfunction; however, this compensation remains imperfect, probably leading to a reduced balance learning capacity in the loneliness-negative group compared to the control group [92]. Additionally, the reduced balance learning in this group may be attributed to: motor and sensory impairments that disrupt the acquisition phase of learning [93], and activation of different neural networks during learning, distinct from those in the control group [94]. These factors may reduce balance learning ability in loneliness-negative patients.

Memory remained intact in both the short-term and long-term phases for PD and control groups. While the basal ganglia influence initial memory consolidation, long-term recall, and the development of automaticity [28, 29], the hippocampus and cerebellum are primarily responsible for initial memory stabilization—a process that gradually consolidates information after acquisition [34], followed by reorganization in the neocortex [34–36]. Previous research suggests that the hippocampus and cerebellum can compensate for striatal dysfunction [91], aligning with our study's finding that PwPD maintained memory over 24 h and one week. Furthermore, consistent with our study, previous research indicates that PwPD can perform complex balance tasks [4, 95] and retain these abilities depending on the task type [96]. These results are preliminary, and we suggest that future studies evaluate the effect of loneliness on balance learning using varied protocols and time frames to more comprehensively assess its impact on motor learning and memory, as well as to investigate potential neural mechanisms.

In our study, relationships between balance, fear of falling, executive function, and anxiety were observed in association with both loneliness and learning parameters, suggesting that loneliness may impair learning by influencing these factors. Previous research indicates that lonely individuals with PD exhibit greater symptom severity—including impaired balance, increased falls, cognitive decline, and psychological problems such as anxiety or depression—compared to non-lonely patients [15, 16]. These factors may adversely affect learning processes [97]. The greater balance impairment and fear of falling associated with loneliness, likely related to postural control dysfunction [98], may specifically hinder balance learning in tasks requiring dynamic postural control, as used in our study. Notably, baseline balance, as measured by stabilometry, did not differ between lonely and non-lonely groups. The only significant difference was observed in the Mini-BESTest scores between loneliness-positive and negative participants. However, this

discrepancy does not compromise our study's results due to our methodological approach. By calculating learning parameters (e.g., learning rate and slope) independently within each group before performing between-group comparisons, we controlled for potential confounders, including baseline balance ability. This strategy ensures valid comparisons of learning parameters across groups. Loneliness is also linked to reduced cognitive function, including deficits in global cognition, executive function, processing speed, and working memory—functions critical to both learning and memory processes such as immediate and delayed recall. Elevated cortisol levels and inflammation, which are implicated in loneliness, may contribute to these cognitive impairments and consequently affect balance learning in PwPD [17–19, 99]. However, as we excluded patients with cognitive impairment, this correlation is unlikely to have influenced our results. Additionally, heightened anxiety, prevalent among lonely individuals, may further impair motor performance and disrupt learning [89]. Anxiety likely diminishes cognitive processing efficiency [100], with negative emotional responses during learning demands placing additional burdens on self-regulation and attentional resources, thereby reducing learning capacity and the retrieval of newly acquired skill [101, 102]. Consistent with this, our study found that anxiety negatively impacts long-term memory. Nevertheless, since loneliness-positive patients exhibited no learning potential, anxiety does not appear to mediate the relationship between loneliness and learning in this context. Therefore, the learning deficits observed in loneliness-positive patients can likely be attributed to loneliness; however, further research is required to confirm this association.

Limitations

This preliminary, cross-sectional study examined the effect of loneliness on a dynamic balance task. To improve generalizability, future studies should employ longitudinal designs to better support clinical applications for improving balance learning in PwPD. This study specifically focused on patients with mild to moderate PD (H&Y stages 1–3) who had no cognitive impairments. Therefore, the findings may not be generalizable to individuals with more severe forms of the disease or cognitive deficits. Future studies should address this limitation by including a broader range of disease severity and cognitive levels. Although anxiety and depression scores did not differ significantly, the trend toward higher scores in the loneliness-positive group, coupled with correlations between anxiety, loneliness measures, and learning parameters, warrants further investigation. Larger studies should examine the effects of loneliness on balance learning in patients both with and without anxiety and depression. Additionally, this study assessed loneliness's impact on learning parameters exclusively in the ON medication state using behavioral measures; future research should include evaluations in the OFF state and incorporate neuroimaging techniques to elucidate underlying mechanisms. Additionally, further studies are needed in diverse populations to confirm the generalizability of these findings to other diseases.

Conclusion

Our findings suggest that loneliness likely impairs balance learning capacity and memory. Although anxiety showed a contributing effect on long-term memory, this is unlikely to be significant given the absence of learning potential in loneliness-positive patients. The observed anxiety effect on long-term memory may be influenced by the study's limited sample size and warrants further investigation.

Clinical trial number

Not applicable.

Abbreviations

PD	Parkinson's disease
PwPD	Patients with PD
QoL	Quality of life
FoF	Fear of falling
H&Y	Hoehn and Yahr
UPDRS	Unified Parkinson's Disease Rating Scale
MoCA	Montreal cognitive assessment battery
HADS-A/D	Hospital Anxiety and Depression Scale
DjG	Dejong Gierveld test
BMI	Body mass index
LED	Levodopa equivalent dose
MiniBESTest	The Mini Balance Evaluation Systems Test
TMT	The Trial Making Test part A and B
VAS-p	The visual analog scale for pain
FSS	The Fatigue Severity Scale
PDFS	The Parkinson's Disease Fatigue Scale
BAI	The Beck Anxiety Inventory
STAT	State-Trait Anxiety Inventory
BDI	Beck Depression Inventory
FESI	The Fall Efficacy Scale-International
PSQI	The Pittsburgh Sleep Quality Index
..	Sleep duration after training and before retention
PDQ-39	39-Item PD Quality of Life Questionnaire
TILS	Three-Item Loneliness Scale
SELSA-PD	The Social and Emotional Loneliness Scale for Adult-PD version
RSI	The Rosenberg Self-Esteem Inventory
MSPSS	The Multidimensional Scale of Perceived Social Support
COM	Center of mass
NASA-TLX	The National Aeronautics and Space Administration-Task Load Index
ANOVA	One-way analysis of variance
LTP	Long-term potentiation
LTD	Long-term depression

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Authors' contributions

Conceptualization: [Mohammad Taghi Joghataei, Ghorban Taghizadeh]; Methodology: [Ghorban Taghizadeh], Data gathering [Seyede Zohreh Jazaeri, Akram jamali], Formal analysis and investigation: [Ghorban Taghizadeh, Seyede

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Data availability
The data supporting the findings of this study can be obtained upon request from the corresponding author. Please note that the data are not publicly accessible due to privacy and ethical considerations.

Declarations

Ethics approval and consent to participate
The authors assert that all procedures conducted in this study adhered to the Helsinki Declaration of 1975, as revised in 2013, as well as the ethical guidelines set forth by pertinent national and institutional committees regarding human experimentation. Participants completed a satisfaction survey. Additionally, the Ethics Committee of Iran University of Medical Sciences granted approval for all procedures involving patients or human subjects (IR.IUMS.REC.1402.497).

Consent for publication
All participants, as well as their legal guardians consented to their responses being published anonymously via the consent form.

Competing interests
The authors declare no competing interests.

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