



Original Research

The Effect of Sensory Reweighting on Postural Control and Cortical Activity in Parkinson's Disease: A Pilot Study



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KEYWORDS

Center of pressure;
Electroencephalography;
Parkinson's disease;
Postural control;
Rehabilitation;
Sensory reweighting;
Virtual reality

Abstract *Objective:* To investigate the effects of sensory reweighting on postural control and cortical activity in individuals with Parkinson's disease (PD) compared to age-matched controls using a virtual reality sensory organization test (VR-SOT).

Design: Cross-sectional pilot study.

Setting: University research laboratory.

Participants: Ten participants with idiopathic Parkinson's disease and 11 age- and sex-matched control participants without neurologic disorders.

Interventions: Not applicable.

List of abbreviations: AP, anteroposterior; COP, center of pressure; EEG, electroencephalography; HC, participant without neurologic conditions; ML, mediolateral; MoCA, Montreal Cognitive Assessment; PD, Parkinson's disease; SOT, sensory organization test; VR-SOT, virtual reality sensory organization test.

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Main Outcome Measures: Changes in center of pressure (COP) and electroencephalography (EEG) activity (ie, power) in the alpha band and the theta/beta ratio recorded during the VR-SOT were the main outcome variables.

Results: PD participants exhibited greater COP displacement, particularly in the mediolateral direction across sensory conditions. They also showed increased alpha power when relying on visual inputs and increased theta/beta ratio power when depending on somatosensory inputs.

Conclusion: PD affects sensory reweighting mechanisms involved in postural control, as evidenced by greater COP displacement and altered cortical activity. These findings emphasize the potential of EEG and VR-SOT in understanding and monitoring postural control impairments in PD.

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Postural imbalance is a hallmark symptom of Parkinson's disease (PD).¹ Several clinical tests, such as the Berg Balance Scale, the Tinetti Balance Test, the BESTest, or the Mini-BESTest, have been developed and validated to identify balance impairments and determine the risk of falls in individuals with PD.² Although these tests include assessments of both static and dynamic postural control,³ they provide limited insights into the specific sensory systems that contribute to postural control.

The sensory organization test (SOT) was designed to quantitatively evaluate the ability to maintain postural control by incorporating visual, vestibular, and somatosensory inputs.⁴ The SOT uses sensory reweighting in which the brain adjusts the relative importance of different sensory systems to sustain balance.^{5,6} This sensory reweighting is compromised in PD, indicating difficulties in distinguishing and selecting reliable information from various sensory systems to ensure postural control.^{4,7} In particular, individuals with PD show increased postural sway when relying predominantly on the inputs of the somatosensory and vestibular systems.⁸⁻¹¹ These studies suggest that individuals with PD exhibit changes in central processing of somatosensory and vestibular information, resulting in increased reliance on vision to maintain balance. However, the cortical processes involved with sensory reweighting of postural control in PD have not been investigated.

Mobile neuroimaging technology is increasingly used to elucidate the cortical processes related to postural control in healthy adults and adults with neurologic conditions.¹²⁻¹⁴ Electroencephalography (EEG) uses electrodes placed on the scalp to measure voltage potential differences between 2 locations on the scalp.¹⁵ These EEG signals can then be decomposed into functionally distinct frequency bands, such as delta (0-4Hz), theta (4-7Hz), alpha (8-12Hz), beta (13-30Hz), and gamma (>30Hz). The activity in these frequency bands is referred to as power. Alpha power and the ratio of slow (theta) to fast wave (beta) activity are of particular interest to study the cortical processes of postural control.^{16,17} Changes in alpha power appear to reflect the sensory and movement-related information processing of postural control.¹⁸ In young adults, occipital alpha power has been shown to increase while standing with eyes closed.^{19,20} Theta/beta ratio power reflects cognitive activity related to attentional control and executive function.²¹ In neurotypical young adults, theta/beta ratio power has been shown to increase while standing with eyes closed and

while standing and performing a dual task.²⁰ In a study of older adults, theta/beta ratio power increased during dual-task standing compared to single-task standing.²¹ In a study of patients with PD with balance impairments, the participants showed decreased mid-frontal and mid-cerebellar theta power while standing with eyes open compared to those with no balance problems and neurotypical older adults.²² These results warrant further assessment to elucidate the cortical processes involved in the sensory organization of postural control in PD.

The primary objective of this pilot study was to investigate the effects of sensory reweighting on postural control and cortical activity in individuals with PD compared to age-matched older adults. We specifically focused on alpha power and the theta/beta ratio as key indicators of the cortical contribution to sensory reweighting in postural control. We hypothesized that individuals with PD would exhibit greater center of pressure (COP) displacement and increased cortical activity during the SOT than older adults.

Methods

Participants

Ten participants with a diagnosis of idiopathic PD were recruited from the Parkinson's Disease and Movement Disorder Clinic at the University of Kansas Medical Center. Eleven age- and sex-matched control participants were recruited from the community. Inclusion criteria were the ability to comprehend and follow instructions in English, ability to stand without assistive devices, scoring >20 on the Montreal Cognitive Assessment (MoCA),²³ and in participants with PD, being in the medication ON state. Exclusion criteria were a diagnosis of severe cognitive impairment or dementia, decreased visual acuity or loss of visual fields that cannot be resolved with corrective lenses, severe head and trunk dystonia or dyskinesia in the medication ON state, blepharospasm, unpredictable motor fluctuations, undergoing deep brain stimulation, and presence of any musculoskeletal conditions which could affect standing and balance activities. This cross-sectional pilot study was approved by the University of Kansas Medical Center Institutional Review Board (#00148555).

Protocol

All participants provided informed consent before starting the study procedures. Relevant demographic information such as age, sex, education level, disease duration, disease severity (measured using the Hoehn and Yahr scale)²⁴ and medication details were extracted from medical records. Medication dose was converted into a levodopa equivalent daily dose.²⁵ The MoCA was administered as a general screen of cognitive function.²³ In addition, we recorded the participant-reported number of falls in the 6 months prior to their visit. All experiments were conducted when participants were in their optimal medication state, about 45 minutes after medication intake.

We used the Virtual Reality Comprehensive Balance Assessment and Training system to administer the virtual reality SOT (VR-SOT).²⁶ The Virtual Reality Comprehensive Balance Assessment and Training system includes a processing computer (Alienware, Dell), a VR-integrated head-mounted device (VIVE Pro Eye^a, HTC), and VR tracking sensors (SteamVR Base Stations^a, HTC). The VIVE Pro Eye features dual organic light-emitting diode displays (2880×1600 pixels) with a 90 Hz refresh rate and a 110° field of view. SteamVR software^b (version 1.13; Valve) links the computer and VR headset. The head-mounted device integrates with an AMTI Optima^c force plate synchronized for precise measurements during the trials (fig 1).

Experimental procedure

Participants were instructed to remove their shoes and socks and stand barefoot on the AMTI Optima force plate. They were asked to position their heel centers 17.5 cm apart with their feet oriented at 14°. Each participant was fitted with a safety harness attached to an overhead anchor for security during testing. A trained spotter was positioned behind each participant to ensure safety throughout the procedure.

The VR-SOT comprises 6 different conditions that mimic the 6 conditions of the Equitest SOT. Condition 1 serves as a benchmark for assessing static balance on a stable surface with fixed VR surroundings. The panels in the VR environment do not move. Participants can use the feedback of the visual, somatosensory, and vestibular systems to keep their balance. Condition 2 provides the same balance testing condition as condition 1, but the VR surroundings are blackened out. Hence, participants must rely on somatosensory inputs to remain upright.²⁷ In condition 3, the surrounding panels are moving in the anteroposterior (AP) direction with a maximum of 20° and a maximum velocity of 15°/s. This condition creates a conflict between normal input from the somatosensory and vestibular systems and the visual information from the moving VR panels. Conditions 4, 5, and 6 mirror the parameters of conditions 1, 2, and 3, respectively, but a foam pad (19×15×1.5inch) is placed between the feet and the force plate, thus challenging the somatosensory system. In condition 4, participants must rely on visual inputs to maintain balance, whereas in condition 5, participants must rely on vestibular inputs.^{27,28} Condition 6 generates a conflict between visual, somatosensory, and vestibular systems.



Fig 1 Demonstration of the Virtual Reality Comprehensive Balance Assessment and Training system with mobile electroencephalography. Left: Participant standing on a firm platform. Right: Participant standing on foam. Participant signed a photo and video release form.

Each of the 6 conditions comprised 3 trials, with each trial lasting 20 seconds. Between each trial, a 5-second break was given. The data from the 3 trials were averaged.

Data capture and processing

The COP data were obtained from the force plate at 200 Hz and processed using MATLAB software^{29,d} to compute the following parameters³⁰:

- ☐ Mean displacement in the AP or mediolateral (ML) direction: the average displacement (mm) of the COP from its mean position in the AP/ML direction.
- ☐ Mean velocity in the AP or ML direction: the average speed (mm/s) at which the COP moves in the AP/ML direction.
- ☐ Average frequency in the AP or ML direction: the rotational frequency (Hz) of the COP as it completes a full circle with a radius equal to the mean displacement.

EEG data acquisition and processing

To capture cortical activity, we used the mobile EXG system^e from Mentalab. Eight electrodes (7 dry brush electrodes on the scalp and 1 flat wet reference electrode) were wired to the Mentalab Explore^e hub attached to the back of the EEG net cap. The Explore device captures the scalp electrical activity at 500 Hz and transmits the signals to a laptop computer via Bluetooth. Electrode placement included the mid-line channels Fz, Pz, Cz, Oz, the frontal channels Fpz and Fp1, the central channel Fcz, and the reference electrode TP10 on the right mastoid, placed according to the international 10-20 system. Impedance was kept below 50 k Ω for the recording. Feasibility testing ensured that placing the VR apparatus over the EEG net cap did not compromise EEG recording.

The EEG data underwent filtering from 0.1-30 Hz using the EEGLAB³¹ plugin within MATLAB software.^{32,d} To reduce noise, EEG recordings were trimmed 10 seconds before the trials began and 10 seconds after the last trial ended. The continuous EEG data were segmented into 6 data sets for each condition. EEGLAB³¹ automatic channel rejection was used to initially detect noisy channels. In detail, the pop_rejchan() function from EEGLAB was used, in which the probability of each EEG channel was calculated as the rejection measurement with z-score threshold of 5. Then, the data were visually inspected to mark those channels with extreme noise. Finally, the Artifact Subspace Reconstruction method³³ from the EEGLAB clean_rawdata plugin (https://github.com/scn/clean_rawdata) was used to reject bad data periods. The standard deviation cutoff for removal of bursts was chosen from 1-20 (mean $\pm$ SD: 8.61 $\pm$ 6.15). The cleaned data were manually inspected again to be included into the power calculation. A data set was excluded from further data analysis if any of its channels was rejected as bad channel. To calculate the theta (4-7Hz), alpha (8-13Hz), and beta (13-30Hz) frequency band power for all 6 conditions, EEGLAB's Spectopo function was used to extract the power spectral density from all electrodes, which uses Welch's method on the 1-second epochs with 50% overlap between its calculation windows.

Statistical analysis

All statistical analyses were conducted using SAS software^f (version 9.4; SAS Institute). The normality of data distributions was assessed using the Shapiro-Wilk test and visual inspection of the histogram and Q-Q plots. We used Fisher exact tests and independent *t* tests to compare demographic and clinical variables between groups.

We calculated differences in sensory reweighting on COP and cortical activity between participants with PD and participants without neurologic disorders (HC) using linear mixed models. We used a random intercept term and a subject-specific coefficient to adjust for correlation between measures within subjects. The linear mixed model included the main effects of group (PD-HC), condition (1-6), and the interaction effect of group $\times$ condition. To minimize the risk of type 1 errors, we only compared (1) condition 2 to condition 1 to evaluate the reweighting of postural control to the somatosensory system; (2) condition 4 to condition 1 to evaluate the reweighting of postural control to the visual system; (3) and condition 5 to condition 1 to evaluate the reweighting of postural control to the vestibular system.^{28,34} We only report the results of the interaction effect. The significance threshold for all analyses was set at $\alpha=0.05$.

Results

Demographic and clinical variables

No differences were found in demographic and clinical characteristics between groups, except for the MoCA score (table 1). Participants with PD scored slightly lower on the MoCA than HC participants. The disease duration and the Hoehn and Yahr stages indicated that participants with PD were in the very mild to moderate stage of the disease.

Initially, our study enrolled 12 participants with PD and 12 control participants. During the postural balance conditions, 2 participants with PD lost their balance and requested support from the spotter. Of those, 1 person with PD

Table 1 Comparison of demographic and clinical characteristics between groups

Variables	PD (n=10)	HC (n=11)	P
Age, y	72.30 $\pm$ 8.77	69.90 $\pm$ 3.27	0.43*
Sex, female: male	3:7	4:7	0.45 [†]
MoCA score (out of 30)	25.20 $\pm$ 2.04	28.27 $\pm$ 1.49	0.0008*
Education, y	15.71 $\pm$ 2.2	14.7 $\pm$ 2.05	0.44*
Disease duration, y	2.11 $\pm$ 3.07	N/A	N/A
Hoehn and Yahr (ON), stage 0:1:2:3	1:2:5:2	N/A	N/A
LEDD, mg/day	298.8 $\pm$ 258.7	N/A	N/A
Falls in previous 6 months, yes: no	5:5	N/A	N/A
Number of falls in previous 6 mo, 0:1:2:3	0:3:1:1	N/A	N/A

NOTE. Continuous variables are expressed as means $\pm$ standard deviations; dichotomous variables are expressed as frequencies.

Abbreviations: HC, participants without neurologic conditions; LEDD, levodopa equivalent daily dose; MoCA, Montreal Cognitive Assessment; N/A, not applicable; PD, participants with Parkinson's disease.

* Independent *t* test.

[†] Fisher exact test.

discontinued in condition 5; the other person with PD lost balance during condition 4 but completed all conditions. One control participant lost balance in condition 4 and discontinued. Data from these participants were excluded from the final analysis. Consequently, the final sample size included in our analyses was reduced to 10 PD and 11 HC participants.

COP variables

COP displacement

The analysis of mean AP displacement demonstrated a significant group by condition interaction effect ($F=8.31$; $P<.001$) (table 2). Post hoc analysis revealed that this interaction was significant for condition 5 (unstable surface, blacked out VR) relative to condition 1 (stable surface, fixed VR), producing a $P<.001$. Participants with PD exhibited greater displacement in the AP direction compared to controls when relying on vestibular inputs to maintain balance (fig 2A).

Similarly, the analysis of mean ML displacement demonstrated a significant group by condition interaction effect ($F=7.25$; $P<.0001$). Post hoc analysis indicated that this interaction was significant for condition 2 (stable surface, blacked out VR; $P=.03$), condition 4 (unstable surface, fixed VR; $P=.002$), and condition 5 (unstable surface, blacked out VR; $P<.0001$) relative to condition 1 (stable surface, fixed VR). Individuals with PD displayed greater ML displacement compared to controls when relying on either somatosensory, visual, or vestibular inputs (fig 2B).

COP velocity

The analysis of AP velocity approached significance for group by condition interaction effect ($F=2.01$; $P=.08$). No post hoc effects were therefore calculated.

The analysis of ML velocity demonstrated a significant group by condition interaction effect ($F=7.64$; $P<.001$). Post hoc analysis indicated that this interaction was significant

for condition 4 (unstable surface, fixed VR; $P<.001$) relative to condition 1 (stable surface, fixed VR). Individuals with PD displayed greater velocity of the COP in the ML direction than controls when the relative contribution of the visual system to postural control was being tested (fig 2D).

COP frequency

The analysis of frequency outcomes did not demonstrate any significant group by condition interaction effects (fig 2E and F).

EEG variables

Alpha power

The analysis of alpha power demonstrated a significant group by condition interaction effect ($F=3.50$; $P=.005$). Post hoc analysis revealed that this interaction was specifically significant for condition 4 (unstable surface, fixed VR; $P=.003$) relative to condition 1 (stable surface, fixed VR). Participants with PD ($5.97\pm 7.23\mu V^2/Hz$) exhibited increased alpha power compared to controls ($3.49\pm 4.41\mu V^2/Hz$) when relying on visual inputs of postural control (fig 3A).

Since participants with PD exhibited cognitive impairment, we repeated the linear mixed model while adjusting for MoCA scores. Although MoCA scores were associated with alpha power ($F=4.59$; $P<.001$), the interaction effect of group by condition remained significant ($F=3.74$; $P=.0007$), with post hoc effects for condition 4 (unstable surface, fixed VR; $P=.0004$) relative to condition 1 (stable surface, fixed VR).

Theta/beta ratio power

Similarly, the analysis of theta/beta ratio power demonstrated a significant group by condition interaction ($F=3.77$; $P=.003$). Post hoc analysis indicated that this interaction was significant for condition 2 (stable surface, blacked out VR; $P=.01$) relative to condition 1 (stable surface, fixed VR). Individuals with PD (5.14 ± 3.27) displayed increased theta/beta

Table 2 Comparison of COP variables across the 6 VR-SOT conditions between PD (n=10) and HC (n=11)

Variable	Groups	MeanAP (mm)	MeanML (mm)	VelAP (mm/s)	VelML (mm/s)	MfAP (Hz)	MfML (Hz)
Condition 1	PD	11.87 $\pm$ 1.12	1.58 $\pm$ 1.08	27.47 $\pm$ 3.88	17.36 $\pm$ 2.77	2.38 $\pm$ 1.75	1.89 $\pm$ 1.02
	HC	4.56 $\pm$ 2.03	1.23 $\pm$ 1.62	20.45 $\pm$ 5.39	11.29 $\pm$ 2.69	0.94 $\pm$ 0.33	1.79 $\pm$ 1.00
Condition 2	PD	25.84 $\pm$ 8.79	11.06 $\pm$ 1.73	29.36 $\pm$ 4.60	17.74 $\pm$ 2.80	2.29 $\pm$ 1.00	2.17 $\pm$ 0.94
	HC	8.43 $\pm$ 5.74	2.42 $\pm$ 1.30	24.25 $\pm$ 5.64	11.76 $\pm$ 2.75	1.05 $\pm$ 0.32	1.65 $\pm$ 0.79
Condition 3	PD	24.52 $\pm$ 7.89	12.93 $\pm$ 1.08	34.65 $\pm$ 16.66	17.47 $\pm$ 2.10	2.29 $\pm$ 0.96	2.06 $\pm$ 0.70
	HC	10.83 $\pm$ 5.46	4.50 $\pm$ 2.26	24.23 $\pm$ 4.47	12.97 $\pm$ 3.54	1.11 $\pm$ 0.25	1.64 $\pm$ 0.61
Condition 4	PD	21.49 $\pm$ 8.59	13.98 $\pm$ 3.77	42.64 $\pm$ 12.53	31.77 $\pm$ 11.00	2.52 $\pm$ 1.51	2.21 $\pm$ 1.23
	HC	6.21 $\pm$ 1.83	4.07 $\pm$ 1.82	22.27 $\pm$ 5.00	12.55 $\pm$ 2.57	0.98 $\pm$ 0.23	1.68 $\pm$ 0.80
Condition 5	PD	44.96 $\pm$ 23.74	19.53 $\pm$ 5.41	41.78 $\pm$ 9.83	23.34 $\pm$ 4.52	2.69 $\pm$ 1.11	2.55 $\pm$ 0.82
	HC	9.49 $\pm$ 5.15	5.25 $\pm$ 1.80	26.33 $\pm$ 5.13	14.46 $\pm$ 3.07	1.67 $\pm$ 0.32	1.68 $\pm$ 0.77
Condition 6	PD	35.14 $\pm$ 15.58	17.09 $\pm$ 4.40	39.41 $\pm$ 15.27	20.36 $\pm$ 3.53	2.02 $\pm$ 1.40	2.10 $\pm$ 0.71
	HC	24.91 $\pm$ 15.58	8.67 $\pm$ 3.74	24.76 $\pm$ 8.47	14.18 $\pm$ 2.78	1.15 $\pm$ 0.33	1.62 $\pm$ 0.52

NOTE. Variables are expressed as mean $\pm$ SD. Condition 1: stable surface with fixed VR surrounding; Condition 2: stable surface with blacked out VR surroundings; Condition 3: stable surface with VR visual conflict; Condition 4: unstable surface with fixed VR surroundings; Condition 5: unstable surface with blacked out VR surroundings; and Condition 6: unstable surface with VR visual conflict.

Abbreviations: COP, center of pressure; HC, participants without neurological conditions; MeanAP/MeanML, mean displacement of the COP in the anteroposterior/mediolateral direction; MfAP/MfML, mean rotational frequency of the COP in the anteroposterior/mediolateral direction; PD, participants with Parkinson's disease; VelAP/VelML: Mean velocity of the COP in the anteroposterior/mediolateral direction; VR, virtual reality; VR-SOT, virtual reality sensory organization test.

ratio power than controls (2.95 ± 2.51) when the relative contribution of the somatosensory system was being tested.

We repeated the linear mixed models while adjusting for MoCA scores. MoCA scores were not associated with theta/

beta ratio power ($F=0.59$; $P=0.79$), and the interaction effect of group by condition remained significant ($F=3.20$; $P=.005$), with post hoc effects for condition 2 ($P=.03$) relative to condition 1.

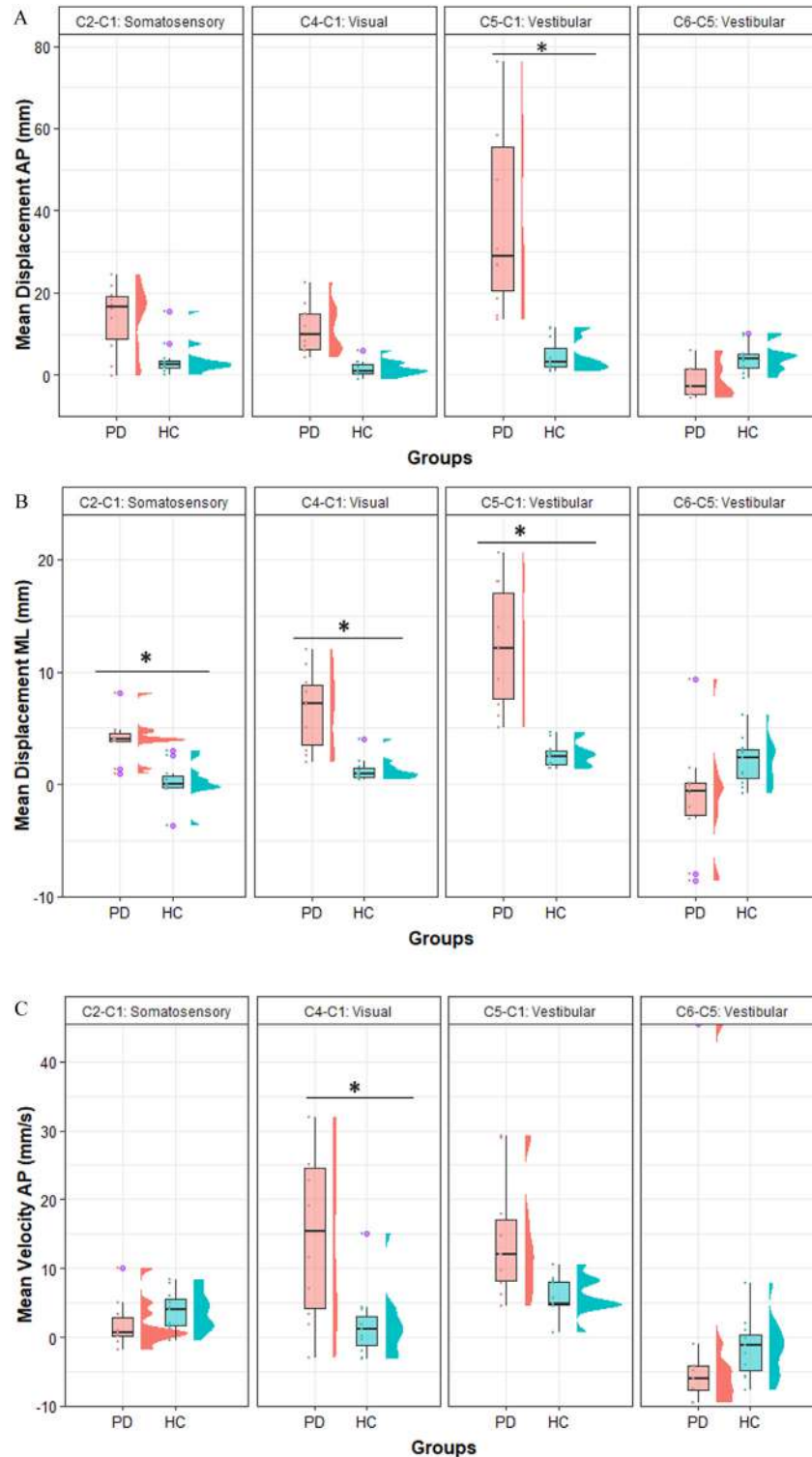


Fig 2 Comparison of center of pressure data using box-and-whisker and raincloud plots between participants with PD (n=10) and HC (n=11). Abbreviations: AP, anteroposterior; HC, participant without neurological conditions; ML, mediolateral; PD, Parkinson's disease.

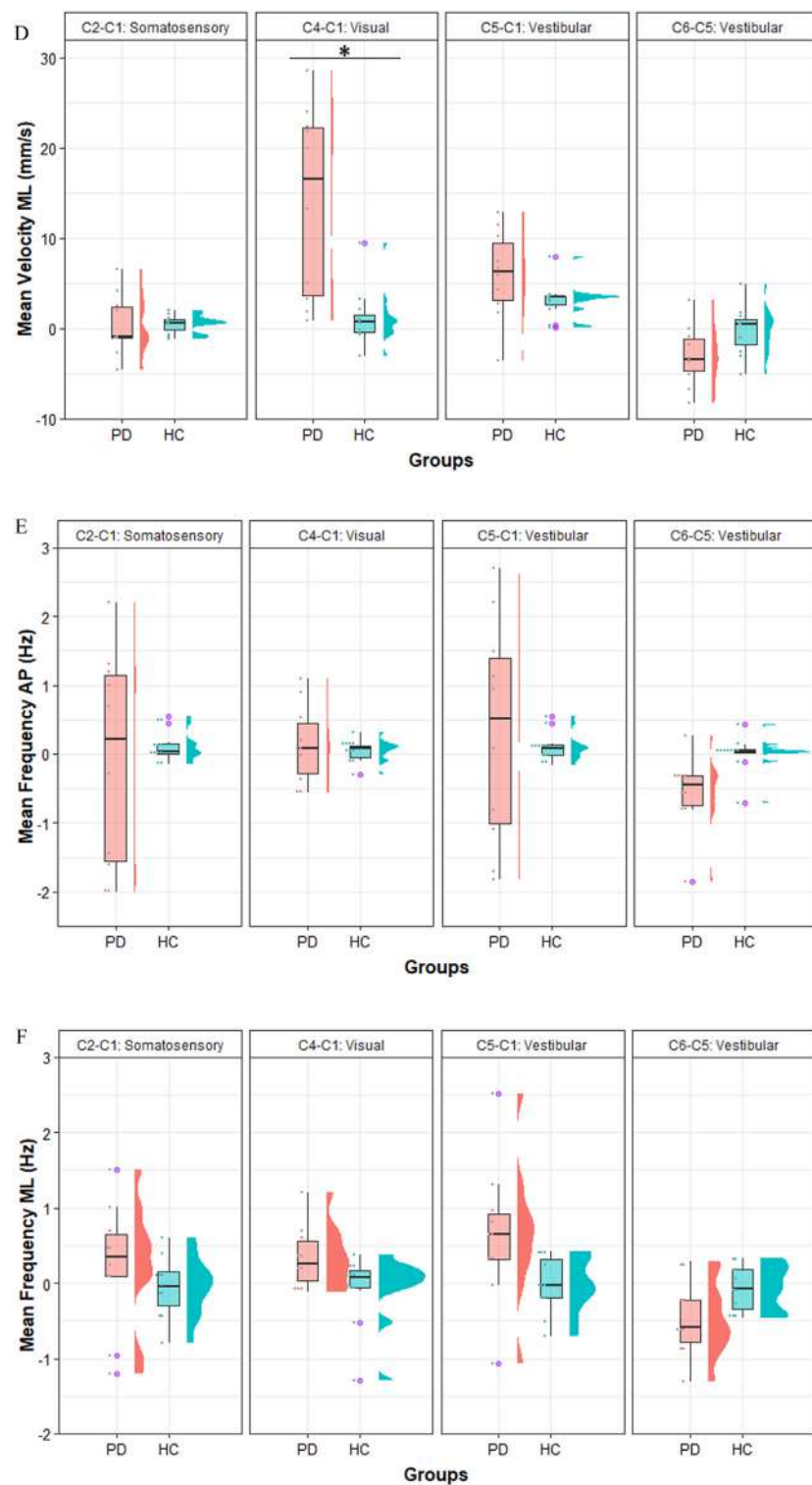


Fig 2 Continued.

Figure 4 shows the topographical maps of alpha power of condition 4 (unstable surface, fixed VR) – condition 1 (stable surface, fixed VR) and theta/beta ratio power of condition 2 (stable surface, blacked out VR) – condition 1 (stable surface, fixed VR) in participants with PD and controls.

Discussion

The purpose of this study was to examine the impact of sensory reweighting of postural control on COP and cortical activity in individuals with PD compared to age-matched

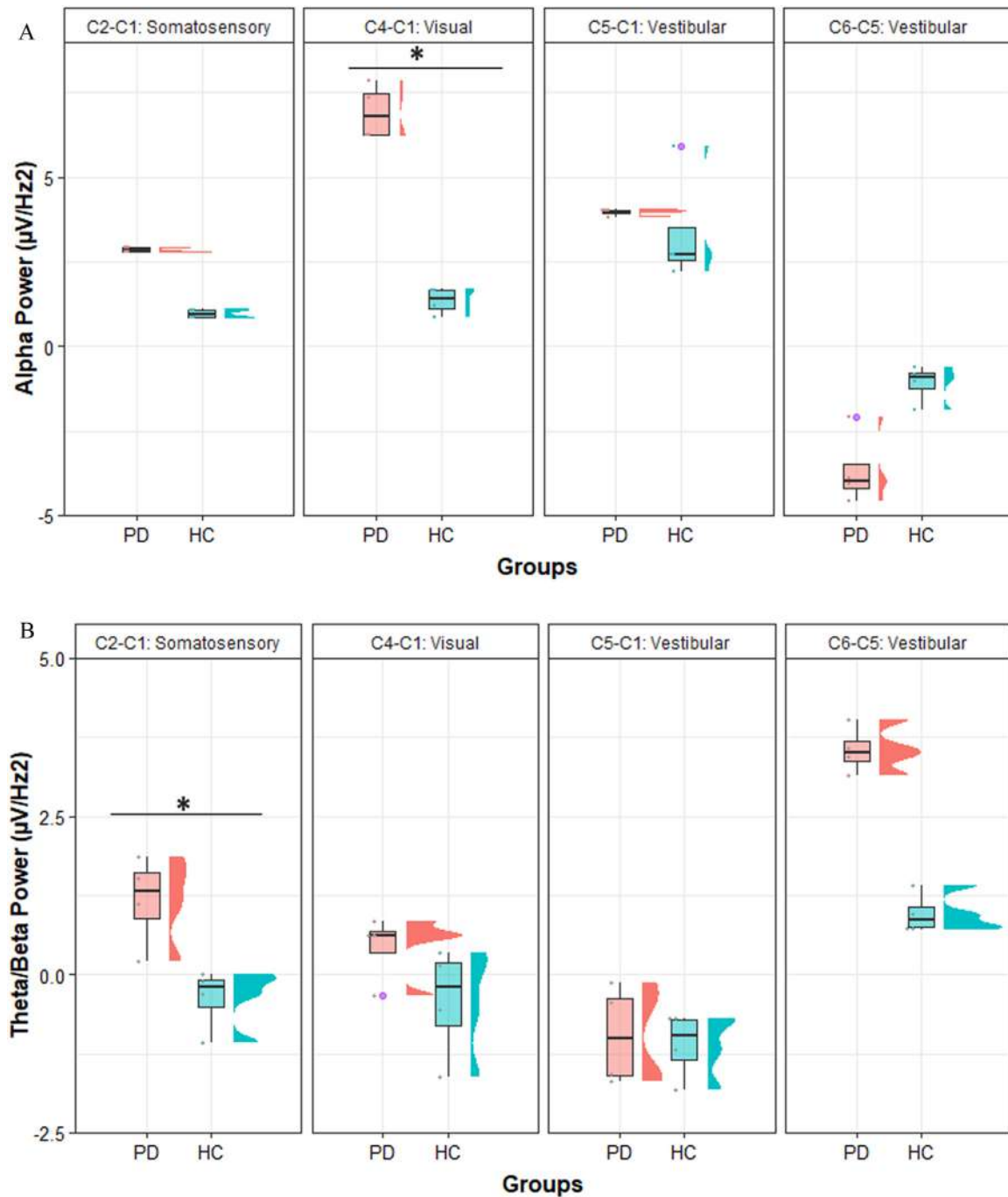


Fig 3 Comparison of EEG power using box-and-whisker and raincloud plots between participants with PD (n=10) and HC (n=11). Abbreviations: EEG, electroencephalography; HC, participant without neurological conditions; PD, Parkinson's disease.

older adults without neurological conditions. We observed 2 key findings: (1) participants with PD displayed greater ML displacement when relying on somatosensory, visual, or vestibular inputs; and (2) participants with PD exhibited greater cortical activity when relying on somatosensory and visual inputs of postural control than HC participants.

Participants with PD exhibited greater COP displacement and velocity particularly in the ML direction, compared to the control group. While increased postural sway in the AP direction is more noticeable with higher postural control task difficulty, both the PD and control groups responded

similarly to sensory adjustments in the AP direction. Previous studies have indicated that individuals in the early stage of PD demonstrated the ability to use sensory inputs for postural control in the AP direction effectively.³⁵⁻³⁷ However, they showed reduced ability to quickly adapt postural control to changing sensory conditions.³⁸ In contrast, individuals with PD showed increased COP displacement in the ML direction when relying on either somatosensory, visual, or vestibular inputs. Previous studies suggest that ML sway is more sensitive than AP sway in detecting postural instability, detecting disease progression, or risk of falls in PD.^{39,40}

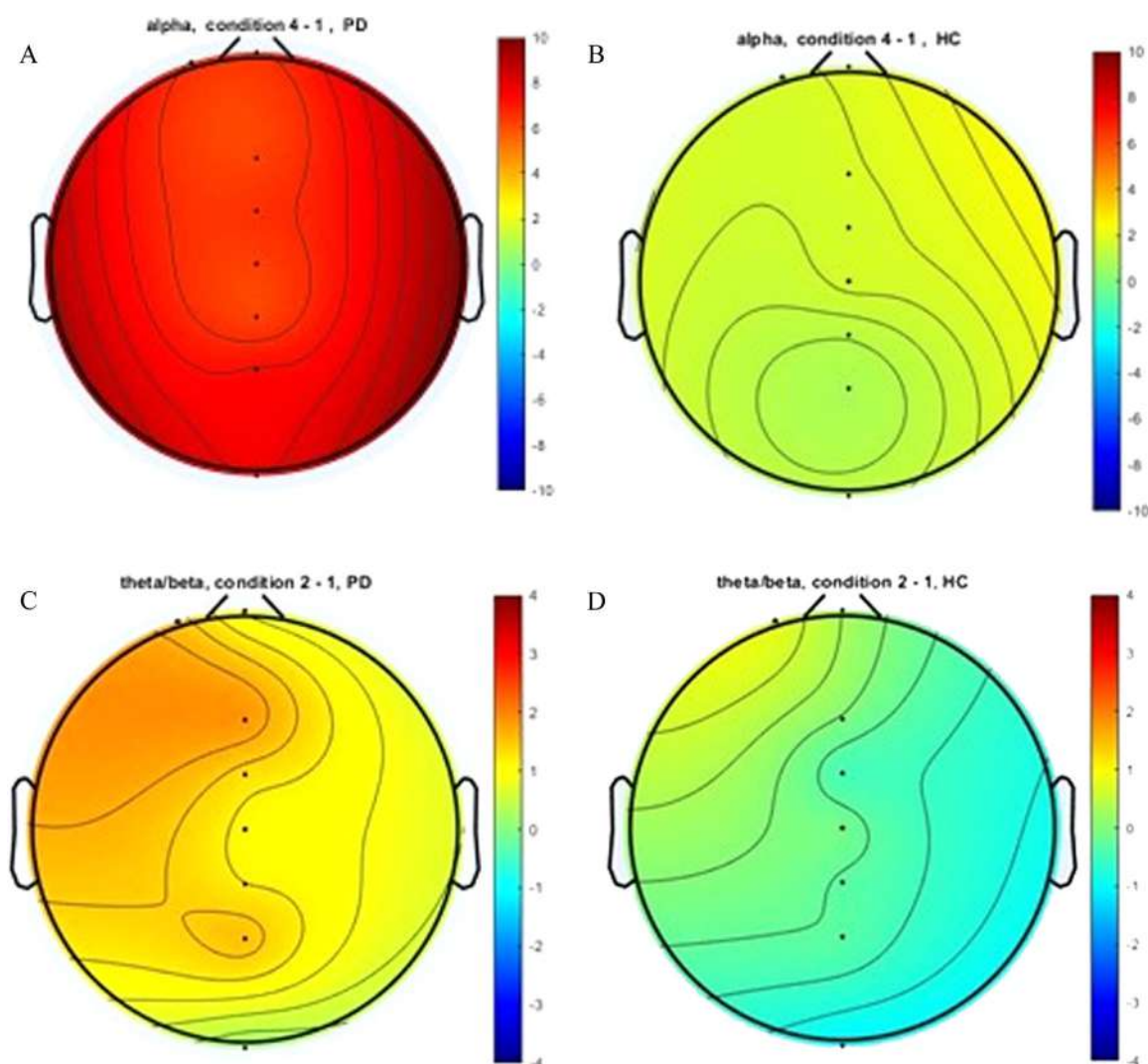


Fig 4 Topographic maps of alpha power ($\mu V^2/Hz$) during visual system testing and theta/beta ratio power during somatosensory system testing in the PD group ($n=10$) and the HC group ($n=11$). Abbreviations: HC, participant without neurological conditions; PD, Parkinson's disease.

We hypothesized that the increased COP displacement during sensory reweighting is linked to increased cortical activity. Indeed, participants with PD exhibited increased alpha power when relying primarily on the visual system, and increased theta/beta ratio power when relying primarily on the somatosensory system for postural control.

Increased alpha power in PD participants when relying on visual inputs suggests heightened cortical activity associated with visual processing. The increased alpha power may reflect either impaired central processing of visual cues or potentially compensating for deficits in other sensory modalities. This finding aligns with the notion that patients with PD may depend more heavily on visual information to maintain balance, due to impaired proprioceptive and vestibular functions.⁴¹ Theta/beta ratio power increased in participants with PD when relying on somatosensory cues.⁴² Occlusion of the dominant visual system likely prompted participants with PD to focus more attention on maintaining postural control, resulting in increased theta/beta ratio power.⁴² In line with the Compensation-Related Utilization

of Neural Circuits Hypothesis (CRUNCH) model,⁴³ individuals with PD might engage additional cortical regions or increase activation in specific areas to compensate for postural control impairments. An alternative explanation for the enhanced cognitive activity may be that participants with PD exhibited mild cognitive impairment. The average MoCA score in the PD group was 25.20, which is below the threshold for normal cognition (≥ 26).⁴⁴ We adjusted for differences in MoCA scores in the statistical analyses. After such adjustment, the increased cortical activity persisted in the PD group. This result implies that difficulties with postural control, independent of changes in cognitive function, are associated with heightened cortical activity in people with PD.

Although preliminary, our findings suggest that COP displacement, particularly in the ML direction, and changes in EEG alpha power and theta/beta ratio could help in the early identification of postural balance impairment and fall risk in individuals with PD. Our findings may also inform the development of targeted interventions, including balance training programs that emphasize sensory integration and

real-time EEG biofeedback to monitor and adjust treatment strategies.

Study limitations

While the study presents the first link between cortical activity and sensory reweighting in PD, caution is necessary due to the relatively small sample size of this study.²⁶ The study may have been underpowered to identify real differences between groups. In addition, the findings may not be generalized to the population of people with PD until the results have been confirmed in a larger sample size. Many VR systems currently on the market (eg, Bertec, Virtualis, UprightVR) or used for research have found the VR-SOT to be valid compared to traditional SOT.^{45,46} However, caution is warranted to directly compare the outcomes of VR-SOT with traditional SOT.⁴⁷ Future studies should encompass larger sample sizes and a wider range of PD severities and subtypes for a more comprehensive understanding of how PD affects cortical processes of sensory reweighting. In particular, the robustness of our findings should be tested in a group of patients with PD with no cognitive impairments. The study results are also sufficiently encouraging to explore the use of EEG as an early marker of balance impairment in PD. Future studies should evaluate the temporal association between changes in cortical activity and balance impairment in PD.

Conclusions

In conclusion, our study provides preliminary insights into the challenges faced by individuals with PD in adjusting postural control in response to changes in sensory inputs, particularly in the ML direction. These exploratory findings underscore the potential role of EEG in detecting subtle changes in cortical activity associated with balance impairments in PD. The increased cortical activity observed in participants with PD when relying on somatosensory and visual inputs highlights the need for further investigation into the neural mechanisms underlying postural control in this population. Future studies are encouraged to build on this foundation, exploring the clinical implications of sensory reweighting and cortical activity changes in PD for improving balance and reducing fall risk.

Suppliers

- a. VIVE Pro Eye and Steam VR Base Stations; HTC.
- b. Steam VR software, version 1.13; Valve Corp.
- c. Optima force plate; Advanced Mechanical Technology, Inc.
- d. MATLAB software; MathWorks.
- e. Mobile EXG system and Explore hub; Mentalab GmbH.
- f. SAS software, version 9.4; SAS Institute.

Disclosures

None.

Data statement

Authors will make available all raw data supporting their conclusions without undue delay.

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