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Parkinson's disease and anticipatory postural adjustments: Decreased cortical activity during step initiation

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ABSTRACT

Background: Step initiation is a critical movement that combines motor and cognitive elements, notably in individuals with Parkinson's Disease (PD) who experience marked difficulties due to disrupted anticipatory postural adjustments (APA). This study investigated the involvement of the Supplementary Motor Area (SMA) and the Dorsolateral Prefrontal Cortex (DLPFC) associated with step initiation that requires high cognitive processing (e.g., cognitive-motor conflicts) in individuals with PD compared to healthy controls.
Methods: We used functional near-infrared spectroscopy (fNIRS) to assess the cortical hemodynamic responses of 33 individuals with PD and 17 healthy controls as they performed step initiation in both congruent (all cues aligned) and incongruent (conflicting cues) conditions. The study sought to analyze variations in the hemodynamic responses related to these conditions, hypothesizing that PD individuals would exhibit reduced cortical activation in the SMA and DLPFC due to motor cortex inefficiencies affecting APA.
Results: Individuals with PD exhibited significant deficits in biomechanical performance (e.g., increased APA delays and errors) and altered hemodynamic responses in the SMA and DLPFC compared to controls, particularly under incongruent conditions. These observations indicate diminished cortical efficiency in PD during motor execution coupled with cognitive demands.
Conclusion: The findings suggest that PD involves impairments in cortical areas linked to movement planning and cognitive control. These findings suggest potential avenues for targeted rehabilitation strategies that enhance cognitive-motor integration, possibly improving mobility and reducing fall risk in PD.

1. Introduction

Step initiation is complex because it integrates motor and cognitive aspects of movement preparation, known as anticipatory postural changes (APA), and movement execution, which refers to the actual step taken. Despite belonging to separate brain circuits [1], the APA and its corresponding voluntary movement are often closely synchronized during stepping. However, the dysfunction of the archetypal APAs is regarded as a significant pathophysiological mechanism that causes difficulties in step initiation in individuals with Parkinson's disease (PD) [2]. Compared to healthy individuals, individuals with PD show a noticeable delay in the sequencing between the initiation of the APA and the onset of the first step [3]. The dissociation between preparation and movement has been interpreted as difficulty releasing a previously inhibited step [4]. In tasks that require conflict resolution and response inhibition, PD individuals step substantially slower and make more mistakes than healthy age-matched controls [5]. This poorer stepping performance in complex environments in individuals with PD is significantly associated with previous falls [5].

Some research on APA control during step initiation shows the

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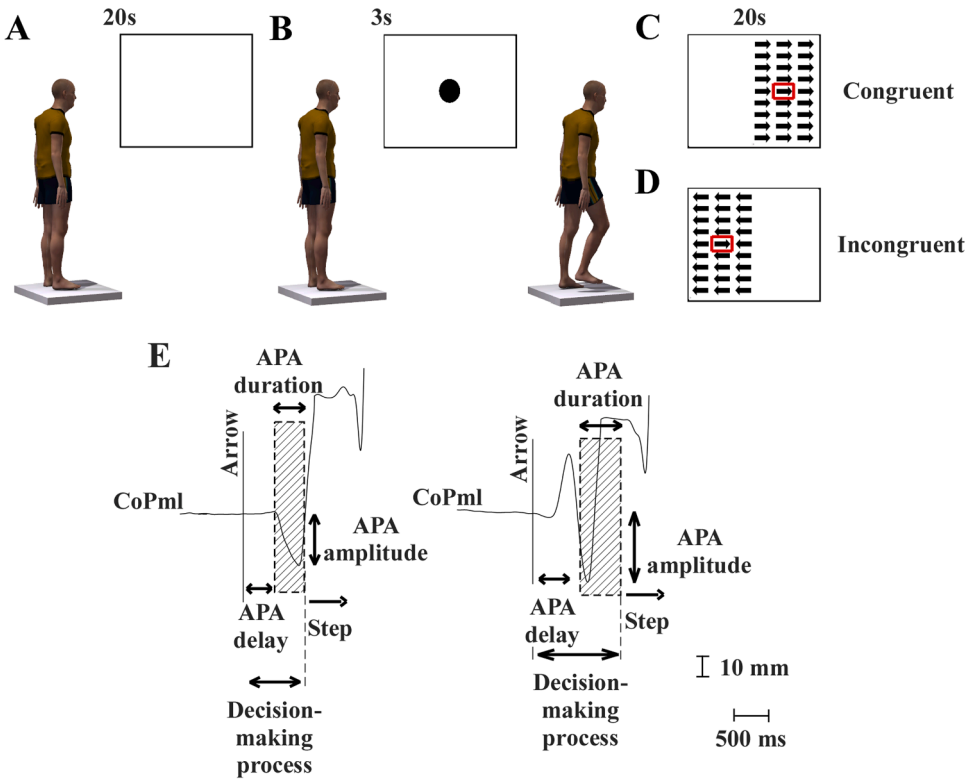

Fig. 1. Sequence of commands presented on the screen. (A) The participant can mentally relax; (B) The participant must mentally prepare for the task; (C) congruent condition, in which all arrows are pointing in the same direction; and (D) incongruent condition, in which the middle arrow is pointing in a different direction than the others. The red squares in panels (C) and (D) were added solely for illustration purposes in the manuscript to help the reader visually identify the central arrow used for step selection. These visual cues were not shown to the participants during the experiment. Participants had to determine the correct stepping direction based on the center arrow when the complete arrows were displayed, coinciding with the auditory "Go" command. (E) Biomechanical variables at the step initiation were analyzed based on the signal from the mediolateral center of pressure (CoPml). The decision-making process interval is between the arrow event's start and the step's start.

involvement of a high level of cognitive processing as the supplementary motor area (SMA) [6–8] and dorsolateral prefrontal cortex (DLPFC) [9]. SMA may inhibit prepotent neural commands during step initiation, which could lead to executing an inappropriate step for the given context [10], and DLPFC is involved in signaling APA errors and cognitive inhibitory process [11]. All these functions are usually impaired in individuals with PD [7,12]. Pelicioni et al. [12] showed that individuals with PD had reduced cortical activity in the DLPFC and SMA during the more complex motor tasks requiring inhibitory control. This may reflect subcortical and/or multiple pathway damage with subsequent deficient use of cognitive and motor resources. However, these studies did not analyze the neural correlates during the decision process and response inhibition in the APA to step initiation in individuals with PD.

This study aims to investigate the participation of SMA and DLPF during the motor-cognitive conflict process in the APA to step initiation, i.e., when inhibition is required to correctly select the step to initiate gait, in individuals with PD compared to healthy age-matched controls. We used functional near-infrared spectroscopy (fNIRS) to assess cortical activity specifically during the decision-making phase of anticipatory postural adjustments, when participants resolved cognitive-motor conflicts during step initiation. Subjects performed a step initiation task designed to impose cognitive-motor conflict. In each trial, a set of arrows was presented, and participants were instructed to respond based solely on the direction of the central arrow. In the congruent condition, all arrows pointed in the same direction, facilitating a straightforward motor response. In the incongruent condition, the central arrow pointed in the opposite direction of the surrounding arrows, requiring participants to inhibit an automatic response and resolve the conflict before initiating movement. This task setup was intended to engage cognitive processes such as response inhibition and motor program selection under conflicting cues—functions often impaired in Parkinson's disease. By targeting these processes, we aimed to investigate how cognitive-motor integration deficits in PD impact both cortical activation and anticipatory postural adjustments during gait initiation. Given that PD affects the function and efficiency of the motor cortex circuitry [13] and worsens APA performance [14,4,15], the hypotheses of this work are: compared with neurologically healthy individuals, individuals with PD (1) would exhibit impaired APA responses and less activity in SMA and DLPFC during incongruent conflictual stepping, and (2) exhibit none or a less pronounced decrease in APA response and activity in SMA and DLPFC during congruent conflictual stepping.

2. Methods

2.1. Participants

Thirty-three individuals with idiopathic PD and seventeen neurologically healthy individuals participated in this study. A neurologist diagnosed PD according to UK Brain Bank criteria. The inclusion criteria for both groups were as follows: >60 years old, not having orthopedic problems, and not presenting cognitive decline - score greater than 19 points on the Montreal Cognitive Assessment [16]. For individuals with PD: mild or moderate stage of the disease (Hoehn & Yahr I, II, or III), no neurological impairment other than PD, or no musculoskeletal changes that could interfere with the execution of the task, and stable medication for at least three months before the visit. We evaluated all individuals without complaints of pain or other motor or sensory conditions that

could limit independence in bipedal posture or interfere with their gait patterns. All procedures were approved by the Ethics Committee of the Federal University of ABC, and written informed consent was obtained from all participants.

2.2. Task

The objective of the task was to assess executive control of inhibition by provoking a cognitive-motor conflict during foot selection for stepping. Initially, the individuals remained standing, with their feet on a force platform, waiting for commands to start the step. The commands were projected on a screen at a distance of 3 m from the participant in the following sequence: (a) a white screen (20 s), indicating for the participant to relax mentally (Fig. 1A); (b) a black circle (3 s), where the patient must mentally prepare for the task (Fig. 1B); and (c) a set of three columns of nine arrows, presented on either the right or left side of the screen for 20 s (Fig. 1C and D). Simultaneously with the arrow display, a recording of the verbal command "Go!" was played. Participants were instructed to quickly identify the direction indicated by the central arrow and initiate the step with the corresponding foot. This involved executing a single, complete step forward with the designated foot, advancing it approximately one foot-length ahead of the initial position and placing it firmly on the ground. Participants were not instructed to raise or lift the leg; a forward step with clear foot placement was required. After completing the step, they remained in position until instructed to return to the starting stance during the subsequent white screen. It is important to note that no visual highlight (e.g., red frame) was presented around the central arrow during the task—the red box shown in Fig. 1 is for illustrative purposes only. For example, if the arrow in the middle of the set points to the right, the step must be started with the right foot. After the 20 s with the arrows and the participant taking the step, the white screen was presented again (20 s), and they had to return to the initial position of their feet (which was marked with adhesive tape). The participant was instructed always to look straight ahead, thus avoiding additional changes in cerebral blood flow. Each participant completed 20 randomized trials, with 10 steps initiated with each foot. As the literature indicates that individuals with PD are not motor asymmetric during step initiation [17], data from both sides were pooled for further analysis.

2.3. Procedures

A skilled and experienced examiner performed PD-specific clinical and cognitive evaluations on the subjects. The clinical characteristics were examined using the Hoehn & Yahr (H&Y), UPDRS-III motor score, and the Montreal Cognitive Assessment (MoCA). Clinical scales and experimental tasks were assessed in the clinically 'on' state approximately 60 min after taking their dose of dopaminergic medication [18], and all assessment sessions were performed individually at approximately the same time of day in the laboratory.

There were two experimental conditions: (1) Congruent, in which all arrows are pointing in the same direction (Fig. 1C), and (2) Incongruent, in which the arrow positioned in the middle of the set points to one side and all the others to the opposite direction (Fig. 1D). Each condition was presented in a separate block lasting approximately 15 min, during which the participant performed 20 trials. In each trial, the participant completed a full step initiation task in response to the arrow cue, followed by a return to the starting position. A 5-minute rest period was provided between the two conditions, and the order of presentation was randomized between participants to control for sequence effects.

2.4. Biomechanical assessment

The participants performed the task on a force platform (40 × 60-cm Optima models; AMTI, Watertown, MA, USA). For kinematic analysis, we placed a reflective marker on the lateral malleolus of both subjects' legs. Twelve optoelectronic cameras (Raptor-4; Motion Analysis Corporation, Santa Rosa, CA, USA) tracked the markers. Kinematic and kinetic data were acquired at a sampling frequency of 200 Hz using a motion capture system (Cortex 6.0; Motion Analysis Corporation, Santa Rosa, CA, USA). A trigger synchronized the motion capture system and the fNIRS system.

The anticipatory postural adjustment (APA) began with the initial lateral displacement of the center of pressure (CoP) toward the leading limb. The end of the APA — marking the beginning of the step — was identified as when the vertical force under the stepping foot began to decrease, indicating weight transfer to the other leg (Fig. 1E) [19].

Data were visually inspected. The variables derived from the force platform included (Fig. 1E): (a) APA delay, the time between the screen with arrows and the beginning of the APA; (b) APA duration, the time between the beginning of the APA and the beginning of the step; (c) APA amplitude, maximum amplitude of the last peak of mediolateral displacement of the CoP before the start of the step; (d) task error percentage: when the participant presents >1 APA or presents 1 APA but starts the step with the wrong leg. To be considered an APA, the peak should be greater than 30 % of the last peak of mediolateral displacement of the CoP before the start of the step. The step amplitude, the distance the stepping foot traveled forward, normalized by foot length, was calculated from these kinematic data.

2.5. Brain function assessment

To evaluate the hemodynamic response of the brain (an indirect measure of brain function), the concentration of oxyhemoglobin (oxy-Hb) and deoxyhemoglobin (deoxy-Hb) was acquired by the NIRSport system (NIRx Medical Technologies, Berlin, Germany) during the task, consisting of 8 LED emitters (wavelengths of 760 and 850 nm) and 8 active photodiode detectors. The cap used has a configuration based on the 10–10 system, and the BOLD signal was recorded from both the dorsolateral prefrontal cortices and the supplementary motor area. The right inferior/middle occipital gyrus was used as a control area, as it is not expected to be modulated by the implemented task. To ensure that the fNIRS cap is placed on each participant's head, we considered the Cz point of the 10–20 system as the reference position. This point is centered between the nasion and inion and the left and right preauricular points. After placing the cap to capture the signal, a thick black cap was also used to adequately cover the optodes, attenuating interference from the environment, light cameras, and optoelectronics. fNIRS data were recorded with NIRStar15–2 software and analyzed offline with nirsLAB v2017.06 (http://www.nitrc.org/projects/fnirs_downstate/).

Data were visually inspected. Channels with a high noise level, with a coefficient of variation (standard deviation/mean) greater than 7.5 % or a gain level equal to 3 (following NIRSport specifications), were rejected. After converting intensity data to optical density, oxy-Hb and deoxy-Hb concentration changes were calculated using the modified Beer-Lambert equation (according to parameters from Gratzer WB, Medical Research Council Labs, Holly Hill London and Kollias N, Wellman laboratories, Harvard Medical School, Boston, MA; http://omlc.ogi.edu/spectra/hemoglobin/summary.html). Statistical channel analysis was performed using an autoregressively bleached robust regression model built into NIRSLab. This analytical approach handles physiological noise and motion artifacts statistically within the general linear model (GLM) without prior data preprocessing. Regressors related to the three types of stimulus presented in each trial were included in the GLM to model the effects of the volunteer's return to the platform (white screen), the preparation stimulus (black circle), and the decision-making process from the beginning of the stimulus (arrows) until the detection of the step initiation movement. The intervals from the start of the step to the start of the white screen (return to the platform) were considered a baseline. A double-gamma canonical hemodynamic response function with a peak time of 6 s was used to make the regressors. These were

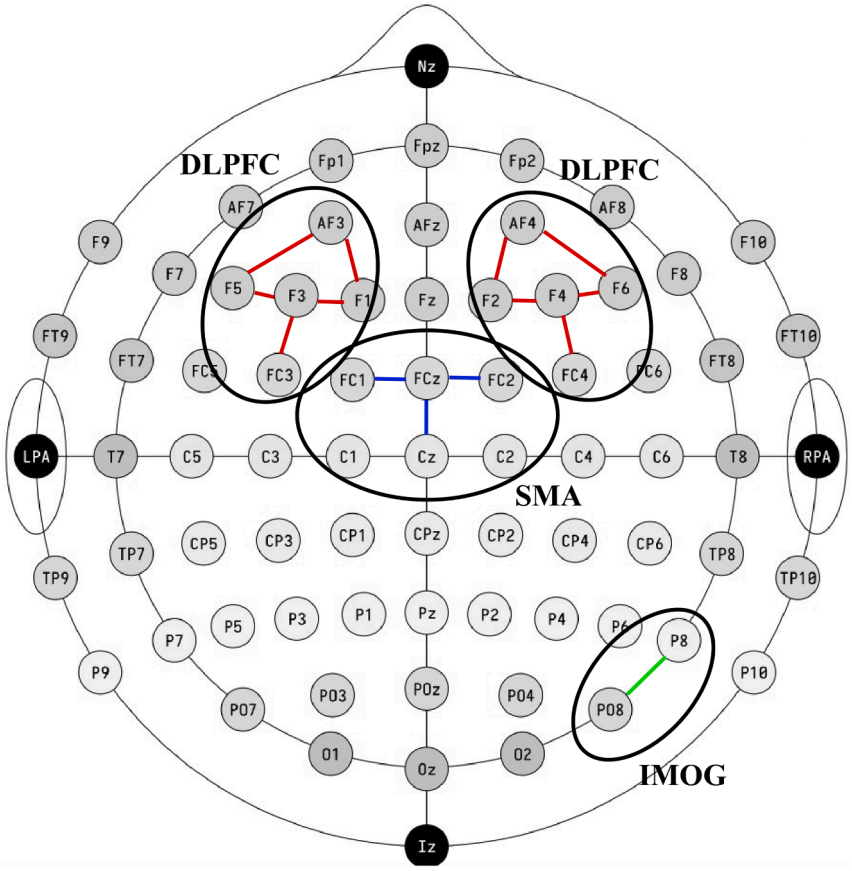

Fig. 2. Representation of the fNIRS cap assembly for collecting the BOLD signal in the Supplementary Motor Area (SMA) and the right and left Dorsolateral Prefrontal Cortex (DLPFC). The infrared light-emitting optodes are in red, and the detectors are in green.

combined with functions defined by the starts and lengths of each type of stimulus. To prioritize step initiation, regressors related to the black-and-white circle stimuli were orthogonalized for the step initiation regressor (decision-making process, Fig. 1E). The right inferior/middle occipital gyrus channel signal was used as a confounding regressor to reduce the effects on blood flow unrelated to brain activity related to the task at hand. A region of interest (ROI-based analysis) was used at the group level. The cortical areas of interest were the Supplementary Motor Area (SMA) and the right and left Dorsolateral Prefrontal Cortex (DLPFC). These regions were selected based on their known roles in motor preparation (SMA) and cognitive control during conflict resolution (DLPFC), allowing us to examine their activation patterns during step initiation (Fig. 2). The first-level analysis results (GLM beta values) related to step initiation were grouped into two ROIs: SMA and DLPFC (formed by the left and right DLPFC channels).

2.6. Statistical analysis

Homogeneity of variances was tested using the Levene test, and normality of data distribution and residuals was assessed with the Shapiro-Wilk test. As no previous consensus exists for selecting the best normalization technique in this context, we adopted an empirical criterion based on the ratio between the Pearson P value and the degrees of freedom (P/df), with values closer to 1 indicating better approximation to normality [20]. This ratio can be compared between the different forms of normalization and indicates which of them the data follows the distribution closest to normal (ratio close to 1). The two-factor analysis of variance (ANOVA) test was used with the normalized data: 2 (group: PD x Healthy) and 2 (condition: congruent x incongruent). The Bonferroni post hoc test analyzed the interactions and differences found in the ANOVA test. The significance level for all analyses was 0.05. The analysis was made using the R program (version 4.1.1) [21].

Table 1
Means (standard deviations) of the characteristics of the participants separately by group.

Characteristics	PD ($n = 33$)	Healthy ($n = 17$)	p-value
Demographic/Anthropometric			
Men / women	24 / 9	10 / 7	0.498
Age (years)	64.76 ± 7.63	63.47 ± 6.46	0.535
Weight (kg)	73.81 ± 12.39	68.96 ± 15.83	0.336
Height (cm)	166.67 ± 8.77	162.24 ± 9.46	0.118
Clinics			
MoCA (score)	22.91 ± 2.89	23.88 ± 2.56	0.229
Mini-BESTest (score)	23.39 ± 5.27	30.35 ± 1.84	0.001
Disease duration (years)	9.15 ± 3.97	–	–
Hoehn & Yahr (escore)	2.33 ± 0.48	–	–
L-Dopa equivalent units ($mg \bullet day^{-1}$)	931.18 ± 441.36	–	–
UPDRS-III (score)	24.36 ± 13.23	–	–

MoCA: Montreal Cognitive Assessment. UPDRS-III: motor score Unified Parkinson's disease rating; Mini-BESTest: Mini-Test of Balance Assessment System scale.

3. Results

3.1. Participants

The groups did not differ in anthropometrics, and only the Mini-BESTest presented lower values for the PD group in relation to the healthy group (Table 1).

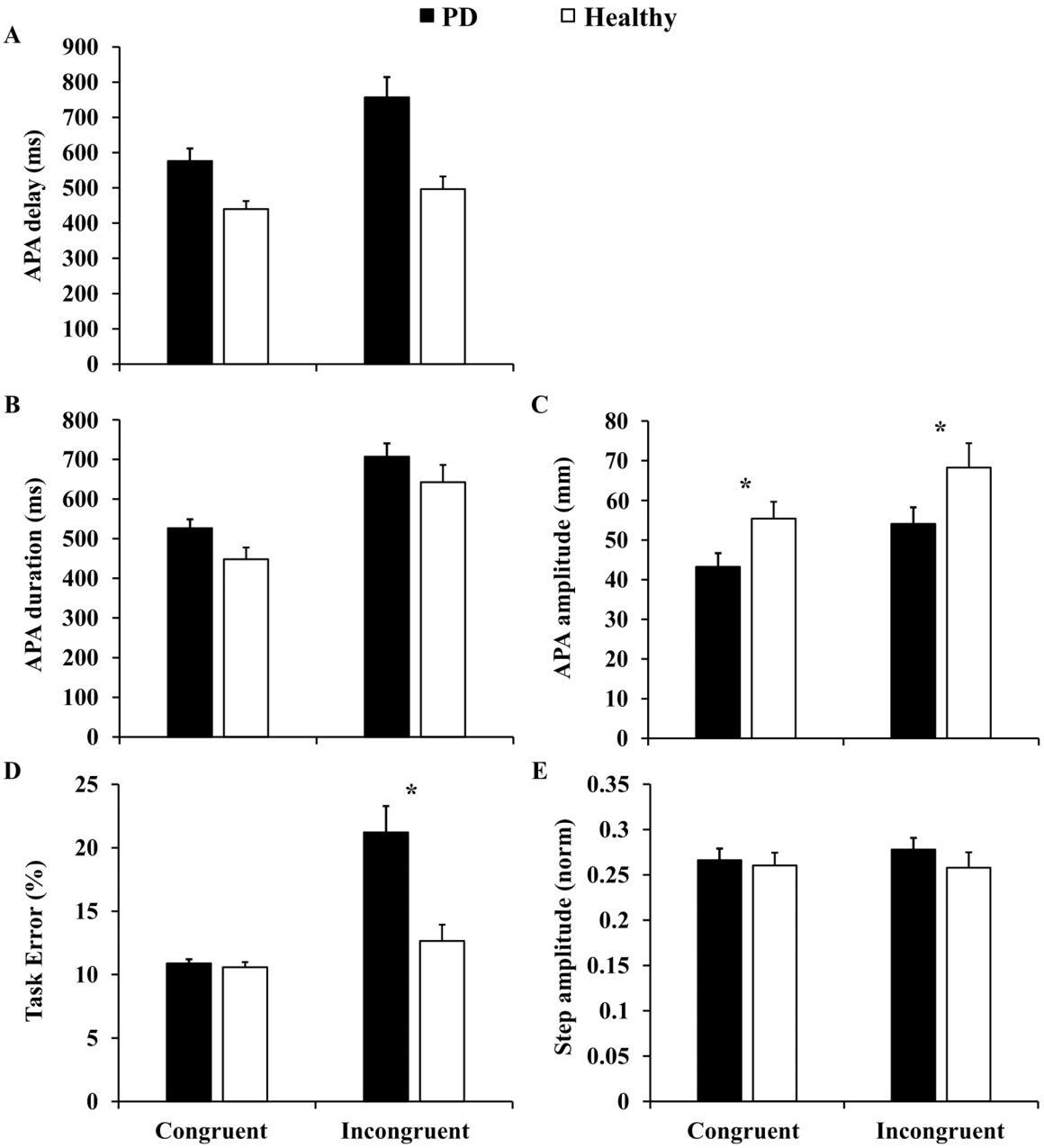

Fig. 3. Mean and standard deviation of biomechanical variables from step initiation. APA: anticipatory postural adjustment. PD: Parkinson's disease. * represents the significant difference between the groups.

3.2. Biomechanical assessment

There was a significant difference in the group factor for the variable APA amplitude ($F_{1,48}$= 4.55, p= 0.038, η^2 = 0.09; Fig. 3C), with lower amplitudes for the PD group (48.65 ± 22.55 mm) in relation to healthy (61.83 ± 22.47 mm).

There was a significant difference in the condition factor for the variables APA amplitude ($F_{1,48}$= 29.09, p= 0.001, η^2 = 0.38; congruent: 47.36 ± 19.92 mm, incongruent: 58.91 ± 25.08 mm; Fig. 3C), and APA duration ($F_{1,48}$= 80.88, p= 0.001, η^2 = 0.63; congruent: 499.70 ± 131.11 ms, incongruent: 684.82 ± 190.27 ms; Fig. 3C), with higher values for the incongruent condition in relation to the congruent condition.

There was a significant group x condition interaction for the variables APA delays ($F_{1,48}$= 5.36, p= 0.025, η^2 = 0.10; Fig. 3A), and task error ($F_{1,48}$= 7.11, p= 0.010, η^2 = 0.13; Fig. 3D). Post hoc comparisons show (1) higher values for APA delays and task error for the incongruent condition in relation to the congruent condition for PD, (2) higher values for APA delays and task error for the PD group in relation to healthy in the incongruent condition.

3.3. Brain function assessment

Evidence indicates that oxy-Hb values are more reliable and sensitive to locomotion-related cerebral blood flow than deoxy-Hb values [22]. Therefore, only the oxy-Hb concentration data are presented. Fig. 4 shows the mean and standard deviation of hemodynamic response for oxy-Hb over SMA and DLPFC. Although Figs. 4 and 5 illustrate task-related changes in oxyhemoglobin (oxy-Hb), they represent different levels of analysis. Fig. 4 shows the raw time series of oxy-Hb concentration changes (in nanomolar) averaged across trials and participants, aligned to stimulus onset, and is intended to illustrate the

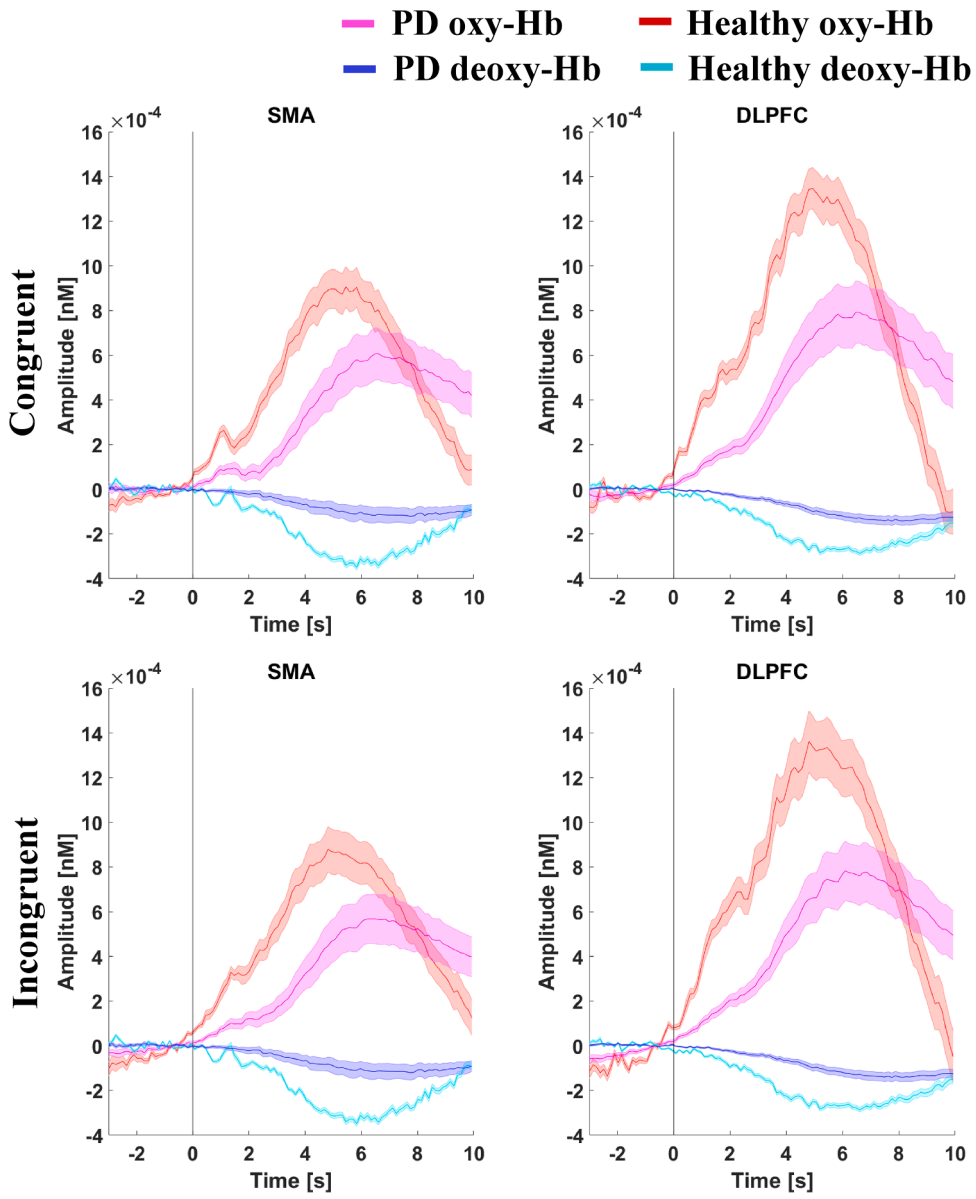

Fig. 4. Time course of the hemodynamic response (mean ± standard deviation) of oxygenated hemoglobin (oxy-Hb) concentration changes in the dorsolateral prefrontal cortex (DLPFC) and supplementary motor area (SMA) for both groups and experimental conditions. The vertical axis indicates relative oxy-Hb concentration changes (in nanomolar, nM), averaged across trials and participants, aligned to the onset of the arrow stimulus. The vertical dashed line marks the moment of arrow presentation and auditory "Go" cue.

temporal profile of cortical activation. In contrast, Fig. 5 presents the beta values derived from the general linear model (GLM), which reflect the estimated amplitude of the task-related hemodynamic response during the decision-making interval (from arrow onset to step initiation). These GLM beta values summarize the activation strength across the task window and are not equivalent to the peak or area under the curve from the raw signal.

There was a significant group x condition interaction for oxy-Hb for SMA ($F_{1,48}$= 8.66, p= 0.005, η^2 = 0.15; Fig. 5A) and DLPFC ($F_{1,48}$= 4.18, p= 0.046, η^2 = 0.08; Fig. 5B). Post hoc comparisons show higher values for the incongruent condition in relation to the congruent condition for PD, and higher values for the PD group in relation to healthy in both conditions.

4. Discussion

Our study evaluated the biomechanical response and hemodynamics of SMA and DLPFC during step initiation with (incongruent) or without (congruent) motor-cognitive conflictual stepping in individuals with PD compared to neurologically healthy individuals. Our results showed a change in biomechanical and hemodynamic responses during the step initiation in individuals with PD in relation to healthy and according to the complexity of the cognitive-motor task. The difference between the conditions were higher APA amplitude, duration, and delays for the incongruent condition than for the congruent condition. The novelty of this study was lower oxy-Hb values for SMA and DLPFC during the decision-making process interval for the PD group compared to the healthy group. Only for the PD group, there were higher oxy-Hb values for SMA and DLPFC for the incongruent condition than the congruent condition.

Our protocol for manipulating cognitive-motor conflict during step initiation was effective in worsening biomechanical responses and altering hemodynamic responses in both groups in the incongruent condition compared to the congruent condition, as previously seen in

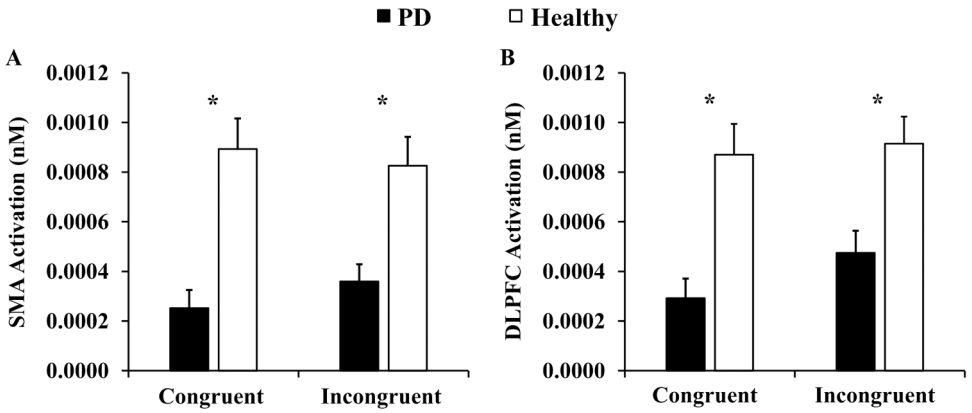

Fig. 5. Mean and standard deviation of task-related activation (GLM beta values) in oxygenated hemoglobin (oxy-Hb) for the Supplementary Motor Area (SMA) and the Dorsolateral Prefrontal Cortex (DLPFC) in both groups and conditions. These values were obtained from the general linear model (GLM) analysis and correspond to the amplitude of the hemodynamic response during the decision-making interval, defined from the onset of the arrow stimulus and auditory "Go" cue to the step initiation. * indicates statistically significant differences between groups or conditions.

other studies [6,4]. We believe that the observed pattern of worse biomechanical responses, particularly the increased APA delays and higher error rates in the incongruent condition among individuals with PD, reflects a disruption in the early selection of the correct motor program. These findings suggest that individuals with PD require additional processing time to resolve the conflicting visual information, inhibit prepotent but incorrect responses, and generate an appropriate motor command. This interpretation is supported by the significant group × condition interactions in APA delay and task error (Fig. 3A and 3D). It aligns with previous evidence indicating impaired cognitive-motor integration in PD during conflict resolution tasks [23]. Furthermore, the ability to make subsequent postural adjustments demonstrates that corrections can be made quickly so that the subject ultimately initiates the step with the correct limb. Studies have found a relationship between cognitive inhibitory control and step initiation performance [6,4,24], hypothesizing the involvement of higher neuronal circuits that control step initiation. Our results support this hypothesis by showing greater hemodynamic activity of the DLPFC in conditions with greater demand for inhibitory control (incongruent condition). Furthermore, our results emphasized the impact of cognitive dysfunctions on the generation of incorrect motor programs when individuals with PD were presented with a cognitive-motor conflict during step initiation.

Our results partially confirm our hypotheses. As expected, individuals with Parkinson's disease exhibited worse biomechanical responses and altered cortical activation patterns compared to healthy controls. Specifically, during the incongruent condition, the PD group showed greater APA delays, increased error rates, and prolonged APA duration, supporting the hypothesis of impaired anticipatory postural adjustments under cognitive-motor conflict. Moreover, individuals with PD demonstrated increased hemodynamic responses in both the SMA and DLPFC during the incongruent condition, suggesting greater neural recruitment in response to task complexity. However, contrary to our original hypothesis of reduced activation in these areas, the increased oxyhemoglobin levels in the PD group, particularly under higher cognitive demands, may reflect a compensatory mechanism rather than diminished activation. Thus, while the biomechanical findings fully support our hypotheses, the cortical activation patterns indicate a more complex, adaptive neural response in PD during cognitively challenging motor tasks.

The impairment of archetypal APAs is an important pathophysiological mechanism that explains impaired gait initiation in PD [2]. Difficulties initiating the step may represent a poor integration of the APA with the swing phase of the step, which could cause freezing of gait [25]. The reduced activation in the SMA and DLPFC in individuals with PD may reflect an insufficient engagement of cortical resources necessary to meet the demands of cognitive-motor integration during step initiation. This finding supports the theory that there is a global impairment of the motor network in PD [26–28], and it does not affect just the basal ganglia but also areas associated with movement modulation. Novaes et al. [27] evaluated the global efficiency of the motor network. They showed that SMA was one of the areas that contributed the most to this decreased motor network connectivity. Therefore, SMA may play an important role in PD physiopathology and should be considered a target in neuromodulation studies.

The results indicate higher oxy-Hb values in the PD group in both the SMA and the DLPFC during the incongruent condition compared to the congruent condition at the step initiation. This suggests that individuals with PD require greater neural resources and effort in these brain regions to manage tasks that involve conflicting or challenging motor conditions. The increased activation in the SMA and DLPFC might reflect compensatory mechanisms to maintain motor control and decision-making processes during complex stepping tasks. These findings highlight individuals' specific neural challenges with PD and underscore the importance of targeted interventions to support these brain areas in improving motor function and overall mobility.

The strengths of this study were (1) we analyzed cortical activity during the decision-making process for step initiation. This interval is when the coupling between posture and gait occurs. Deficits in these intervals suggest that basal ganglia mechanisms for preparing a motor program in advance of step initiation might be disrupted [29]. (2) We analyzed the hemodynamic response during step initiation using the control channel of the inferior/middle occipital gyrus. Even though short-distance channels were not used, the control channel in the visual region should reduce these extracerebral effects, which suggests that hemodynamic responses are related to brain activity.

The main limitation of our study is that individuals showed high diversity regarding the use of daily medications that can alter cerebral circulation. However, all groups used these medications. Our results can be interpreted with caution, considering the above caveat.

In conclusion, our study provides valuable insights into the complex interactions between cognitive and motor functions during step initiation in individuals with PD compared to neurologically healthy individuals. We demonstrated that a cognitive-motor conflict exacerbates biomechanical and hemodynamic differences, highlighting the sensitivity of SMA and DLPFC to these conditions in the PD population. Our findings underscore the importance of considering cognitive elements in assessing and treating motor dysfunctions in PD. The results also suggest that targeted interventions aimed at enhancing cognitive-motor integration could ameliorate some of the motor symptoms experienced by

Patient consent Statement

All participants provided written informed consent prior to participation in the study, in accordance with the Declaration of Helsinki. The study protocol was approved by the Federal University of ABC Ethics Committee, and participants were informed about the research's objectives, procedures, risks, and benefits. They were assured of the confidentiality of their data and their right to withdraw at any time without penalty.

these patients.

CRediT authorship contribution statement

Luana dos Santos de Oliveira: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Claudia Eunice Neves de Oliveira:** Writing – original draft, Methodology, Data curation, Conceptualization. **Layla Cupertino Salloum e Silva:** Writing – original draft, Methodology, Data curation. **Emanuele Los Angeles:** Writing – original draft, Methodology. **Nathalia Mendes Pellegrino:** Methodology. **Vanessa Milanese:** Writing – review & editing. **João Ricardo Sato:** Writing – review & editing, Data curation. **Fabio Augusto Barbieri:** Writing – original draft, Data curation. **Daniel Boari Coelho:** Writing – review & editing, Supervision, Project administration, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

None.

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