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Influence of Cognitive Task Difficulty in Postural Control and Hemodynamic Response in the Prefrontal Cortex during Static Postural Standing

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Abstract: In daily life, we perform several tasks simultaneously, and it is essential to have adequate postural control to succeed. Furthermore, when performing two or more tasks concurrently, changes in postural oscillation are expected due to the competition for the attentional resources. The aim of this study was to evaluate and compare the center of pressure (CoP) behavior and the hemodynamic response of the prefrontal cortex during static postural standing while performing cognitive tasks of increasing levels of difficulty on a smartphone in young adults. Participants were 35 healthy young adults (mean age ± SD = 22.91 ± 3.84 years). Postural control was assessed by the CoP analysis (total excursion of the CoP (TOTEX CoP), displacements of the CoP in medial–lateral (CoP-ML) and anterior–posterior (CoP-AP) directions, mean total velocity displacement of CoP (MVELO CoP), mean displacement velocity of CoP in medial–lateral (MVELO CoP-ML) and anterior–posterior (MVELO CoP-AP) directions, and 95% confidence ellipse sway area (CEA)), the hemodynamic response by the oxyhemoglobin ([oxy-Hb]), deoxyhemoglobin ([deoxy-Hb]), and total hemoglobin ([total-Hb]) concentrations using a force plate and functional near-infrared spectroscopy (fNIR), respectively. The results showed that the difficult cognitive task while performing static postural standing caused an increase in all CoP variables in analysis ($p < 0.05$) and of [oxy-Hb] ($p < 0.05$), [deoxy-Hb] ($p < 0.05$) and [total-Hb] ($p < 0.05$) compared to the postural task. In conclusion, the increase in the cognitive demands negatively affected the performance of the postural task when performing them concurrently, compared to the postural task alone. The difficult cognitive task while performing the postural task presented a greater influence on postural sway and activation of the prefrontal cortex than the postural task and the easy cognitive task.

Keywords: postural standing; dual-task; difficulty; fNIR; center of pressure

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1. Introduction

Postural control is considered a complex motor skill that integrates postural equilibrium and postural orientation. It results from the interaction of multiple and dynamic sensorimotor processes, somatosensory, vestibular, visual, and neuro-musculoskeletal systems, necessary to maintain an appropriate balance and perform different tasks [1]. Evidence suggests that postural control depends on attentional resources beyond automatic processes; these attentional requirements can depend on age, postural task, nature of the cognitive task, and balance skills [2].

In daily life, we are constantly performing several tasks simultaneously. When performing two or more tasks, the attention is divided between both tasks, which results in performance declines in one or both tasks (dual-task interference). The dual-task paradigm is an approach used in various studies to assess the relationship between attention and postural control [2].

There are three theories commonly used to explain the dual-task interference or the limitation of attentional resources while performing a dual-task: capacity sharing, bottlenecks or task switching, and cross-talk [3]; however, there is no consensus about the underlying mechanisms of the dual-task interference [4].

Postural control has been evaluated under the dual-task paradigm to understand the role of cognitive processes; most studies assessed static or dynamic postural control as a primary task and cognitive task as a secondary task [2,5–7].

Keeping balance during a static standing posture while performing other tasks is practiced regularly on a daily basis. Maintaining an upright stance appears to be practically automatic without requiring attention; however, prior studies showed that postural control during standing posture is influenced by cognitive tasks performed simultaneously [8,9].

Previous studies reported divergent results in the influence of cognitive tasks on postural control while performing a static standing posture in young adults. For example, some studies revealed that the postural sway was reduced in dual-task conditions compared to the standing postural (single-task) [10–12]. Conversely, others indicated greater postural sway in dual-task conditions compared to the single-task [13].

As available evidence suggests that postural control depends on attentional resources beyond automatic processes to complement and help understand these controversial results about the influence of the dual-task on postural control, it becomes relevant to analyze the cortical activation during the execution of postural motor tasks. Brain activity analysis during static and dynamic postural control tasks has emerged from neuroimaging studies using functional magnetic resonance imaging (fMRI) [14], electroencephalography (EEG) [15], positron-emission tomography (PET) [16,17], and functional near-infrared spectroscopy (fNIRS) [18].

The fMIR, fNIR, and PET are neuroimaging techniques that depend on neurovascular coupling, while EEG detects the brain's electrical activity [19]. The fMIR and PET record brain activity in all cerebral regions while performing motor imagery or virtual reality tasks [18,20], so they cannot be used during natural tasks, such as walking or standing while performing other tasks in real-time.

The fNIRS has some advantages compared to other neuroimaging techniques, such as portability, motion tolerance, and low cost [19]. It is an optical neuroimaging technique that is based on hemodynamic responses of neuronal cortical tissues, measuring changes in oxygenated and deoxygenated hemoglobin concentrations in the active brain regions [21,22].

The prefrontal cortex has an essential role in various brain functions, such as memory, attention, executive function, other cognitive functions [23], and cognitive postural dual-task performance [24].

Previous studies that assessed prefrontal cortex activation during dual-task conditions found an increase in brain activity in the prefrontal cortex during dual-task compared to postural single-task [25]. However, others suggest a diminution in cortical activity when the cognitive task load increases [26].

Many studies use the fNIR to analyze the prefrontal cortex [18]. Given the applicability of fNIR in recording the brain activity in real-time task performance and the importance of the prefrontal cortex in motor control and cognitive functions, we have chosen the fNIR to measure the changes in hemoglobin concentrations in the prefrontal cortex in this study.

It is important to combine the analysis of cortical activity derived from fNIR signals with postural control analysis to study neuromotor control processes, so as to predict risk factors for falls and the developing cognitive diseases [18]. With this in mind, and considering the ambiguous results of dual-task studies, this study aimed to better understand the influence of attentionally demanding cognitive tasks with different difficulty levels during a simple postural task (static postural standing) using a force plate for the center of pressure analysis. Most of these studies assessed stability postural using center of pressure measures, fNIR for prefrontal cortex activation analysis, and dual-task cost (DTC) to analyze the dual-task interference (determine the cognitive task interference on stability postural).

Using smartphones during postural and walking tasks while performing secondary tasks is common in daily life. However, few studies evaluated the effect of smartphone use on postural stability while performing upright standing [27]. For this reason, and to contribute to an ecological approach to studying dual-task performance, we examined dual-task performance on postural control by maintaining a quiet standing posture while performing a smartphone cognitive task with different difficulty levels. Furthermore, smartphone use is more frequent among young adults [28], and many studies carried out in this group have shown that excessive smartphone use has negative health effects [29,30]. Therefore, it is essential to study the cognitive functions and postural control in young adults to implement early strategies to help reduce accidents or injuries using smartphones and cognitive disturbances at more advanced ages.

We hypothesized that: (i) the young adults would demonstrate a decline in postural control performance and an increase in prefrontal cortex activity when performing the difficult dual-task compared to the easy dual-task and postural single-task; (ii) the dual-task cost in postural stability would be higher when young adults were performing a difficult cognitive task than an easy cognitive task.

2. Materials and Methods

2.1. Participants

The sample size was calculated using G*power software (Franz Faul, Edgar Erdfelder, Axel Buchner, Universität Kiel, Kiel, Germany, version 3.1.9.6) based on the study design, in an $\alpha = 0.05$ and statistical power of 0.95. Therefore, a minimum of 18 individuals were needed to achieve a large effect size (Cohen's $f = 0.40$).

Thirty-five young adults (mean age ± SD = 22.91 ± 3.84 years; 23 males and 12 females) were recruited to participate in this study. We recruited young, healthy adults between 18 and 35 years and free of musculoskeletal problems, injuries, or disorders affecting balance, neurological diseases, or sensory/visual/hearing impairments. The study was publicized in reseachers' networks, and the volunteers contacted the researchers.

Anthropometric data were collected for all the participants (age, height, body mass; for participants' characteristics, see Table 1). The study was conducted according to the Declaration of Helsinki. All participants provided written informed consent forms. The study was approved by the Ethics Committee of the Polytechnic Institute of Coimbra (approval number: 27_CEPC2/2019).

Table 1. Anthropometric and demographic characteristics of the sample (mean ± SD; %).

Variables		Sample n = 35
Age (years)		22.91 ± 3.84
Height (m)		1.72 ± 0.09
Body mass (Kg)		73.89 ± 16.19
BMI (Kg/m^2)		24.85 ± 4.03
Gender (%)	Male	n = 23; 65.7%
	Female	n = 12; 34.3%

BMI: body mass index.

2.2. Task Protocol

Postural task (single-task): Participants stood comfortably on the force plate with their feet shoulder-width apart, eyes open, and arms along the trunk during 60 s [31,32].

Cognitive single-task: The cognitive task consisted of an arithmetic and visual–spatial memory task [33] with two different challenging levels (easy and difficult) [34,35] presented on the participant's smartphone screen in which the participant verbalized the answer during 60 s.

The easy cognitive single-task consisted of adding and subtracting calculations with one digit (e.g., 3 + 2 = ?; 7 + ? = 9) and memorizing the color of each figure displayed on the smartphone screen.

The difficult cognitive single-task consisted of adding and subtracting calculations with one or two digits (e.g., 56 + 23 = ?; 7 + ? = 85) and memorizing each figure's color, number, and the image displayed on the smartphone screen.

The number of correct and incorrect answers was recorded. Then, we measured accuracy as a percentage of correct responses from the given answers to determine cognitive performance.

In dual-task conditions, participants were to maintain the postural task while performing an easy cognitive task on the smartphone (easy dual-task) and the other dual-task consisted of maintaining the postural task while performing a difficult cognitive task on the smartphone (difficult dual-task, Figure 1).

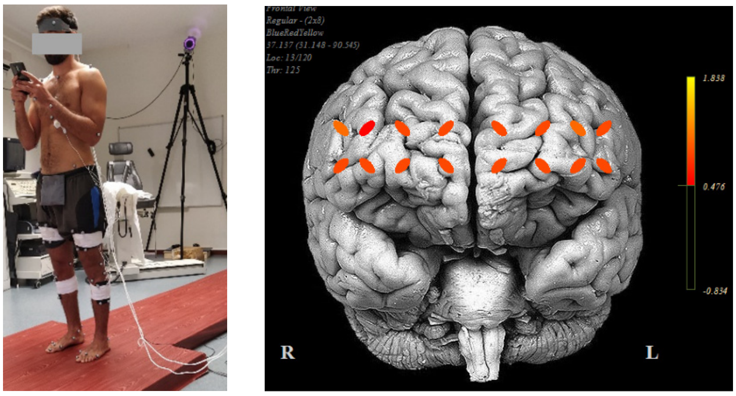

Figure 1. Prefrontal cortex activation (oxyhemoglobin) during difficult dual-task performance.

The cognitive single-task (easy and difficult) was performed while sitting on a chair as a reference measure for cognitive performance. It was also performed while the participants maintained postural tasks (dual-task).

Participants performed all tasks with the fNIRS equipment attached to the forehead. The changes in oxy and deoxyhemoglobin concentrations relative to a 10 s baseline were recorded immediately before performing each task. Then, the following conditions were performed during which prefrontal cortex oxygenation was recorded for 60 s: cognitive single-task (easy and difficult: sitting on the chair), postural task (standing on force plate), and the cognitive and postural tasks concurrently (dual-task: easy and difficult). All tasks were performed twice during 60 s; between each task, there was a rest period of 45 s [18]. The participants were not advised which task to prioritize during the dual-task, and the order in which the tasks were performed was random.

The participants used their personal smartphones and held them as usual to maintain ecological validity. However, through qualitative visual analysis, the smartphones' dimensions were similar.

2.3. CoP Analysis

The Bertec® force plate model FP4060-07-1000 (Bertec Corporation, 6171 Huntley Road, Suite J, Columbus, OH, USA) was used to collect COP behavior. More specifically, the total excursion of the center of pressure (TOTEX CoP–unit in mm), the displacements of the center of pressure in medial–lateral (CoP-ML–unit in mm) and anterior–posterior (CoP-AP–unit in mm) directions, the mean total displacement velocity of CoP ((MVELO

CoP–unit in mm/s), the mean displacement velocity of CoP in medial–lateral (MVELO CoP-ML–unit in mm/s) and anterior–posterior (MVELO CoP-AP–unit in mm/s) directions, and 95% confidence ellipse sway area (CEA–unit in mm^2), were assessed in the present study. These data were filtered using a 50 Hz low-pass filter, a 7th order Butterworth, and they were processed after the assessment with a Matlab routine (version R2020b, The Mathworks, Inc., USA).

2.4. fNIR Data Acquisition and Analysis

A fNIR100A-2 (Biopac System Inc., Goleta, CA, USA) device was used to assess the brain activation in the prefrontal area. This particular device records at a frequency of 2 Hz with 16 recording channels with a source–detector separation of 2.5 cm. It measures oxy-Hb and deoxy-Hb (unit in μ mol/L) changes with two peak wavelengths at 730 nm and 850 nm.

For data acquisition and analysis the COBI Studio (v1.2.0.111) and fNIRSoft professional (v3.3), respectively, were used (Biopac software).

Before performing each task, participants were asked to relax and not think about anything for 10 s to collect the baseline changes in oxy-Hb and deoxy-Hb.

First, a visual inspection to eliminate low-quality channels was performed. The raw files were filtered with a low-pass finite impulse response (FIR) filter, with an order of 20 Hamming, and a cutoff frequency set at 0.1 Hz to remove long-term drift, high-frequency noise, and cardiac and respiratory cycle effects [36,37]. Afterwards, to remove motion artifacts the sliding-window motion artifact rejection (SMAR) algorithm was used (window size= 10 s, upper threshold = 0.025 nm, lower threshold = 0.003 nm) [36]. The changes in light absorption were converted to changes in concentration of oxy-Hb and deoxy-Hb using the modified Beer–Lambert Law concerning a 10 s local baseline recorded at the beginning of data collection and a differential pathlength factor (DPF) = 6 [18]. The total hemoglobin (total-Hb) also was assessed by [total-Hb] = [oxy-Hb] + [deoxy-Hb].

2.5. Dual-Task Interference

The dual-task cost (DTC) evaluated cognitive and motor interference (dual-task interference) expressed as a percentage change in performance during dual-task (DT) relative to single-task (ST) conditions using the following equation [38]:

$$\mathrm{DTC} = \frac{\mathrm{DT} - \mathrm{ST}}{\mathrm{ST}} * 100\%$$

The DTC was calculated for postural control stability (CoP analysis) and cognitive performance (accuracy of percent correct answers) at different cognitive difficulty levels ($\mathrm{DTC}_{\mathrm{easy}}$ and $\mathrm{DTC}_{\mathrm{difficult}}$). Positive DTC values for CoP reflected a decrement in performance of a DT (increased postural instability) relative to the performance of a postural task (single-task), while negative values indicate benefices (decreased postural instability) in DT performance compared to the postural task. Conversely, a positive percentage in DTC for cognitive performance demonstrated an increase in accuracy (increased percentage of correct answers) during DT relative to the performance of a cognitive single-task, while negative DTC values indicate cognitive performance deterioration in DT compared to ST.

2.6. Statistical Analysis

Data were analyzed with IBM SPSS Statistics 25.0 software for Windows (SPSS, Inc., Chicago, IL, USA). Homogeneity of variances and normality of the distribution of the parameters was tested with Levene's and Shapiro–Wilk's test, respectively. Each of the variables, the hemodynamic responses ([oxy-Hb], [deoxy-Hb], [total-Hb], and the CoP variables, were compared in the different tasks (postural task versus DT (easy and difficult)) with a Friedman test with Bonferroni-corrected post hoc tests for pairwise comparations.

DTC was calculated for each CoP parameter (TOTEX CoP, CoP-ML, CoP-AP, MVELO CoP, MVELO CoP-ML, MVELO CoP-AP, CEA) using the equation described above. DTC cognitive task performance using the percentage of correct answers was also calculated for the DT (easy and difficult) using the same equation. The differences between DTC easy and difficult for each cognitive and motor performance analysis were determined with the Wilcoxon signed-rank test.

Statistical significance was set at the level of $p < 0.05$.

3. Results

3.1. Cognitive Task Performance

Young adults increased the percentage of correct answers from the cognitive single-task (easy and difficult) to both dual-task conditions (Figure 2). The differences were of statistical significance between the difficult cognitive single-task and difficult dual-task ($p = 0.004$).

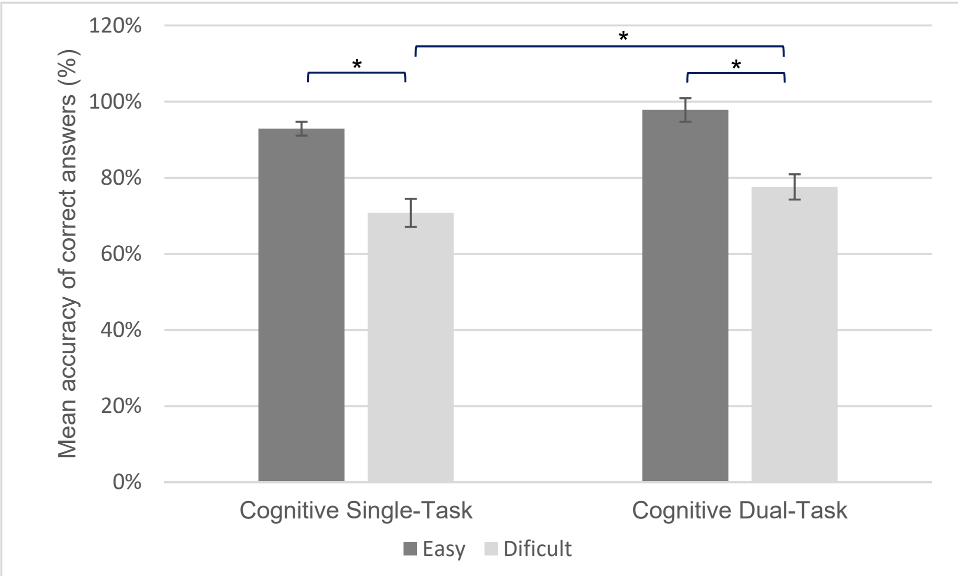

Figure 2. Mean accuracy and standard errors (error bars) of the percentage of the correct answers during cognitive single-task and dual-task. * $p < 0.05$-significant difference between difficult cognitive single-task and difficult dual-task, easy and difficult cognitive single-task, easy and difficult dual-task; not statistically significant between easy cognitive single-task and easy dual-task (Wilcoxon signed-rank test).

The percentage of correct answers in the difficult cognitive single-task and difficult dual-task was smaller than in the easy cognitive single-task and easy dual-task. These differences between easy and difficult cognitive single-task performance ($p < 0.001$), and easy and difficult dual-task ($p < 0.001$) performance, were significant.

3.2. Postural Control

Analysis showed significant differences for all parameters of CoP (total excursion, displacements of the CoP in medial–lateral and anterior–posterior, mean total velocity displacement, mean velocity displacement of CoP in medial–lateral and anterior–posterior, and 95% confidence ellipse sway area) between the postural task and dual-task with two different challenging levels ($p < 0.001$, see Table 2).

Table 2. Comparisons of CoP behavior among the postural task (ST), easy and difficult dual-task, median (IQR).

Outcomes	Single-Task	Easy DT	Difficult DT	*p*-Value [1]
TOTEX CoP	2428.4 (2194.1–2873.0)	2635.6 (2311.7–3033.2)	2610.2 (2411.9–3123.8)	<0.001 *
CoP-AP	1837.5 (1648.6–2186.1)	1960.6 (1779.8–2309.5)	2028.2 (1817.7–2338.2)	<0.001 *
CoP-ML	1221.0 (1075.9–1427.9)	1319.9 (1170.1–1529.2)	1282.2 (1204.1–1497.6)	<0.001 *
CEA	224.6 (150.7–425.6)	724.1 (236.2–1303.7)	674.5 (326.2–1786.8)	<0.001 *
MVELO CoP	485.7 (438.9–574.7)	527.2 (462.4–606.7)	522.1 (482.4–624.8)	<0.001 *
MVELO CoP-AP	367.5 (329.7–437.2)	392.1 (356.0–461.9)	405.7 (363.6–467.7)	<0.001 *
MVELO CoP-ML	244.2 (215.2–285.6)	264.0 (234.0–305.9)	256.5 (240.8–299.5)	<0.001 *

TOTEX CoP, total excursion of the center of pressure (mm); CoP-AP, displacement of the center of pressure in anterior–posterior direction (mm); CoP-ML, displacement medial–lateral direction (mm); CEA, 95% confidence ellipse sway area (mm^2); MVELO CoP, mean total velocity displacement of CoP (mm/s); MVELO CoP-AP, mean velocity displacement anterior–posterior of CoP (mm/s); MVELO CoP-ML, mean velocity displacement medial–lateral of CoP (mm/s); ST, single-task; DT, dual-task. [1] Friedman test; * $p < 0.05$.

Post hoc analyses showed a significant increase for all CoP variables during dual-task performing compared to the postural task (TOTEX CoP: ST versus easy DT: $p < 0.001$; ST versus difficult DT: $p < 0.001$; CoP-AP: ST versus easy DT and ST versus difficult DT: both $p < 0.001$; CoP-ML: ST versus easy DT: $p = 0.001$; ST versus difficult DT: $p < 0.001$; CEA: ST versus easy DT and ST versus difficult DT: $p < 0.001$; MVELO CoP: ST versus easy DT and ST versus difficult DT: $p < 0.001$; MVELO CoP-AP: ST versus easy DT and ST versus difficult DT: $p < 0.001$; MVELO CoP-ML: ST versus easy DT: $p = 0.004$; ST versus difficult DT: $p < 0.001$). However, no significant differences among easy dual-task and difficult dual-task were found (all CoP variables: $p > 0.05$).

3.3. Hemodynamic Changes in the Prefrontal Cortex

The changes in hemoglobin concentrations (oxy-Hb, deoxy-Hb and total-Hb) in the prefrontal cortex during the postural task and dual-task (easy and difficult) performance are presented in Figure 3.

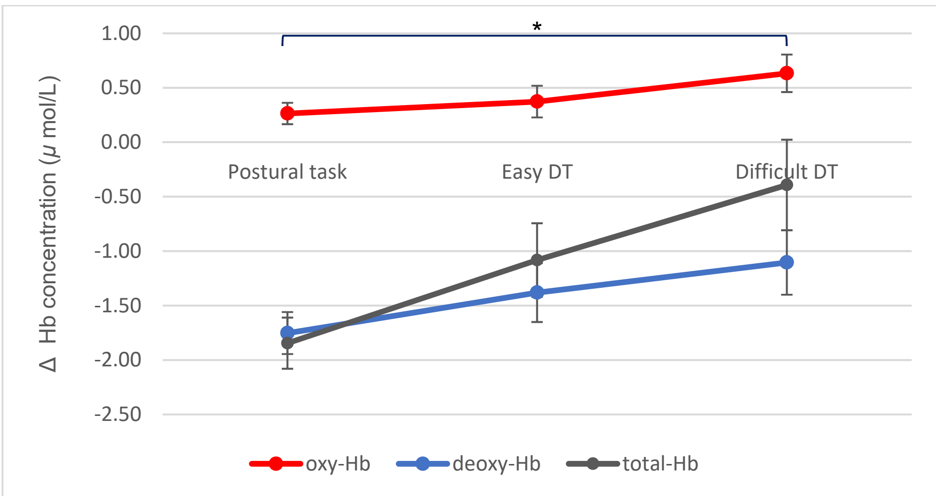

Figure 3. Changes in hemoglobin concentrations in the prefrontal cortex during the postural task and dual-task (easy and difficult) performance. The y-axis displays relative concentration (median values and standard error (error bars)) changes of hemoglobin (Hb in μ mol/L). The x-axis displays tasks performance: postural task (single-task), easy DT (easy dual-task), difficult DT (difficult dual-task). The oxyhemoglobin concentration, [oxy-Hb], is indicated by the red line, the deoxyhemoglobin concentration, [deoxy-Hb], by the blue line, and total hemoglobin concentration, [total-Hb], by the grey line. * $p < 0.05$ in changes [Oxy-Hb], [deoxy-Hb] and [total-Hb] between the difficult dual-task and postural task (Friedman test with Bonferroni correction).

The oxy-Hb concentration increased from the postural task to both dual-task conditions and from easy dual-task to the difficult dual-task ($p = 0.032$), although hemodynamic changes for oxy-Hb values were only observed between the postural task and difficult dual-task ($p = 0.026$).

For deoxy-Hb values, there were significant differences between the postural task and dual-task with two different challenge levels ($p = 0.001$). However, the post hoc analyses showed a significant difference only between the postural task and difficult dual-task ($p = 0.001$).

There were significant differences in the total-Hb between the postural task and both dual-tasks ($p < 0.001$). The post hoc analyses showed a significant difference between the postural task and easy dual-task ($p = 0.026$), and the postural task and difficult dual-task ($p < 0.001$). However, no significant differences were found between the easy and difficult dual-task ($p = 0.167$) in total-Hb.

3.4. Dual-Task Interference

There was an improvement in the cognitive performance during dual-task (postural task while performing a cognitive task) than cognitive single-task (seated) conditions ($DTC_{easy} = 6.7\%$ and $DTC_{difficult} = 13.9\%$). In addition, relative to cognitive performance, the difference between DTC_{easy} and $DTC_{difficult}$ was significant ($p = 0.047$).

Positive DTC values were found in all CoP variables under analysis, reflecting a postural stability deterioration from the postural task to the easy and difficult dual-task due to cognitive task interference. For CoP variables, the $DTC_{difficult}$ values were slightly higher than DTC_{easy} values; however, the difference was not significant (DTC_{easy} vs. $DTC_{difficult}$: $p > 0.05$ for all CoP variables).

4. Discussion

The aim of this study was to evaluate and compare the CoP behavior and the hemodynamics response of the prefrontal cortex during dual-task performances of increasing levels of cognitive difficulty using the smartphone in young adults.

The CoP impairments (postural instability) and the activation of the PFC were increased with the more demanding cognitive task during the dual-tasks performances compared to the postural task.

In the cognitive–motor dual-task interference analysis by DTC, young adults showed a pattern of cognitive priority trade-off [39] with improvements in cognitive task performance and deterioration in all COP parameters during both dual-task conditions (easy and difficult) compared to postural and cognitive single-tasks.

Greater center of pressure sway was observed in more challenging conditions (dual-task) than the postural task, showing that the young adults prioritized the concurrent task (cognitive task) under dual-task conditions. Furthermore, performing a concurrent cognitive task (easy and difficult) in static standing posture negatively affected postural control, and the differences in the CoP variables were significant between the postural task and the easy dual-task and the postural task and the difficult dual-task. However, the increase in cognitive load was not reflected in a significant difference in postural control between the dual-tasks with different demanding levels (easy DT versus difficult DT). Furthermore, the DTC for each CoP variable showed that the difficult cognitive task had slightly more interference in postural stability deterioration than the easy cognitive task; however, this difference was not significant.

Another indicator that young adults prioritized the cognitive task over postural control was the percentage of change in cognitive task performance from cognitive single-task to dual-task. The accuracy of correct answers was higher during dual-task than cognitive single-task. However, the increase in the accuracy of correct answers was only significant between the difficult cognitive single-task and difficult dual-task.

The present study demonstrated that the oxy-Hb, deoxy-Hb, and total-Hb concentrations during the difficult dual-task performance were higher than in the easy dual-task and postural task (single-task). However, only the oxy-Hb and deoxy-Hb concentrations differed significantly across the postural task and difficult dual-task. On the other hand, significant differences were found in total-Hb concentrations between the easy dual-task and postural task, and the difficult dual-task and postural task.

The hemodynamic response usually reflects an increase in [Oxy-Hb] and a decrease in [deoxy-Hb]. The increase in the oxyhemoglobin concentration is related to increased cerebral blood volume in response to cortical activation; but is more confounded with physiological factors (e.g., heart rate, respiration); and the deoxyhemoglobin is more robust to systemic changes [40]. Our results showed changes in [Oxy-Hb], [deoxy-Hb] and [total-Hb] during the difficult dual-task compared to postural task, demonstrating an increase in neural activity, possibly due to the higher load of the cognitive task. To our knowledge, we did not find other studies that report this difference in all these parameters using the fNIR device, especially during the simple postural task (static standing postural).

A study demonstrated an increase in the brain activity in the high working memory span group during dual-task compared to the low working memory span group. The authors suggested that in the low working memory span group, the changes in the brain activity may have been difficult to detect due to low working memory capacity and the postural task to be more challenging (one leg standing) [25]. Another study showed that the frontal brain activation during the dual-task (walking while performing a cognitive task) was associated with the cognitive load during gait and not a response to verbalizing words [41]. Our results also showed a significant increase in prefrontal activity during difficult dual-task. However, this change was found during a simple postural task (static standing posture), suggesting that the brain activity increase can be independent of the levels of difficulty of the postural task and be more related to cognitive demands.

The total excursion, displacements of the CoP in medial–lateral and anterior–posterior, mean total displacement velocity, mean displacement velocity of CoP in medial–lateral and anterior–posterior directions, and 95% confidence ellipse sway area were negatively affected during easy and difficult dual-task performance compared to the postural task. Our study is in line with previous research. For example, a study showed that the center of pressure path length, 90% confidence area, and maximum CoP speed were significantly affected by the use of different smartphone functions (talking, texting, and sending a text message on the smartphone) in young adults [31].

A recent systematic review and meta-analysis about the effect of cognitive task complexity on dual-task postural stability suggest that the cognitive task complexity cannot determine a positive or negative change in postural stability during quiet standing in healthy young adults [42]. The outcomes analyzed in this review included the center of pressure sway area, sway velocity, sway variability, total sway path length, and sway frequency, but not including hemodynamic response in the prefrontal cortex analysis. We also used similar CoP variables to analyze postural stability during dual-task. In the difficult dual-task compared to postural task, our results showed an increase in brain activity in the prefrontal cortex and postural instability, and an increase in cognitive performance, demonstrating an increase in attentional resource competition among cognitive and postural tasks; and that postural control is not an automatic process. Contrarily, most studies included in recent systematic review and meta-analysis referred to non-significant changes in cognitive performance during dual-task in static standing postural and reported that postural instability occurs when postural tasks are more challenging [42].

Another previous study has also shown that young adults under dual-task conditions increased their cognitive performance. However, in oxyhemoglobin concentration and CoP sway path (total, AP, and ML) did not find changes from the single-task (standing) to dual-task in young adults [24]. The differences in cognitive demands during the postural task may explain the inconsistency between these and our results.

The bottleneck theory can explain the postural stability deterioration during the difficult dual-task performance due to the need to share the same neural or cognitive resources. On the other hand, the capacity sharing theory can explain the interference between cognitive and postural tasks because there was an increase in cognitive performance and a decline in postural performance, possibly because both require common limited resources [3,33].

This study's essential strong point was to evaluate the differential effects of cognitive tasks with different difficulty levels while performing postural standing simultaneously by analyzing the center of pressure, hemodynamic response in the prefrontal cortex, and cognitive–motor dual-task interference. Regarding the level of cognitive task difficulty, the choice of tasks proved to be adequate since the young adults had a significantly better cognitive performance in the easy cognitive task than in the difficult cognitive task in both single and dual-task conditions.

In our study, the postural task was performed without a smartphone, based on previous studies [31,43,44]. However, some studies reported an increase in postural instability due to head position in the frontal plane [45,46]; for that reason, we recommend postural analysis in following studies and the addition of a single-task in which the participants hold the smartphone when standing.

Although we processed the fNIR data, we could have added complementary measures (e.g., blood pressure, heart rate, respiratory cycle, etc.) to monitor systematic changes since oxyhemoglobin is sensitive to physiological changes.

A study that used the EEG showed that the cognitive emotion regulation strategies are associated with working memory, cognitive function, and visual/sensory perception [47]. Thus, it would be interesting to integrate the fNIR and the EEG (hemodynamic changes and electrical activity of the brain) to investigate the interaction between emotions and cognitive and motor performance during the dual-task, especially in depression and anxiety conditions, negative and positive emotions in athletes.

It would also be interesting, in future studies, to incorporate the muscular activity in the lower limbs for muscular synergy analysis, the non-linear analysis of the center of pressure to complement the CoP linear analysis, and to include a multichannel fNIR device to cover other brain regions beyond the prefrontal cortex.

Concerning the reduced postural stability found under dual-task conditions in our results, we recommend dual-task training [6] in clinical practice to help reduce accidents or injuries caused by the negative effects of smartphone use on postural control. Furthermore, the cognitive–motor dual-task training, including different tasks, can improve motor and cognitive performance [48].

5. Conclusions

This study showed that dual-tasking performance with different levels of challenge influences CoP behavior and hemodynamic response in the prefrontal cortex in healthy young adults. The increase in the cognitive demands negatively affected the performance of the postural task when performed concurrently, compared to the postural task alone. Maintaining the postural task while performing a difficult cognitive task on the smartphone proved to be more challenging due to increased postural instability and the hemodynamic response in the prefrontal cortex.

Under both dual-task conditions, young adults improved their cognitive task performance and increased their postural instability, suggesting the prioritization of the cognitive task over the postural task.

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