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Original Paper

Cognitive Load Modulates Brain-Body Association in Hypertension During
Dual-Task Standing: An fNIRS Study

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Abstract

27 Background: Hypertension is associated with cognitive decline and impaired postural
28 control; yet, its effects on brain-muscle coordination during cognitively demanding
29 balance tasks remain unclear.

30 Methods: Twenty participants with hypertension (HT) and eighteen normotensive
31 controls (NT) completed six standing tasks with progressively increasing balance and
32 cognitive demands. Postural stability was assessed using center of pressure (COP),
33 cortical activation using functional near-infrared spectroscopy, and lower-limb muscle
34 activity using surface electromyography.

35 Results: Cortical oxyhemoglobin responses did not differ significantly between
36 groups across task conditions (adjusted $P > 0.05$). Under the most demanding
37 condition, the HT group exhibited substantially greater postural sway, including larger
38 COP sway area, total path length and mediolateral displacement ($P < 0.05$),
39 accompanied by increased activation of the left rectus femoris and right tibialis
40 anterior ($P < 0.05$). Correlation analysis revealed distinct neuromotor control
41 strategies: NT participants showed negative associations between sensorimotor
42 cortical activation and COP measures, indicating efficient sensorimotor integration,
43 whereas HT participants demonstrated positive associations between premotor
44 cortical activation and muscle activity, consistent with compensatory muscle
45 recruitment.

46 Conclusions: Hypertension is associated with a shift in postural control from efficient
47 cortex-COP coupling to compensatory cortex-EMG coupling under high cognitive
48 load. These findings suggest that hypertension may alter brain-body coordination
49 during challenging postural control, leading to greater reliance on compensatory
50 muscular recruitment.

51 Trial registration: Chinese Clinical Trial Registry ChiCTR2600116874;

52 Keywords: hypertension, cognitive function, postural control, balance, fNIRS,
53 brain-muscle coupling

1. Introduction

Hypertension is one of the most prevalent chronic cardiovascular diseases worldwide, affecting approximately 1.4 billion adults, with fewer than one-quarter achieving adequate blood pressure control[1]. Beyond increasing cardiovascular risk, chronic hypertension is associated with structural and functional brain abnormalities[2], including white matter lesions, cerebral microvascular dysfunction, and cortical reorganization, which contribute to impairments in attention, executive function, and sensorimotor integration[3-5]. These neurological alterations may ultimately compromise postural control and increase the risk of falls.

Balance control is a highly complex dynamic process that relies on the integration of vestibular, proprioceptive, and visual information, while being modulated by higher-order cognitive resources, particularly executive control functions[6]. Research has shown that with advancing age, individuals experience a decline in motor and balance functions, which may be associated with alterations in prefrontal cortex activation patterns[7]. Postural stability depends on cognitive functions mediated by the prefrontal cortex[8]. In addition, other brain regions, including the parietal lobe[9], temporal lobe, and cerebellum[4], also play a role in cognitive function. Previous studies have demonstrated that under single-task conditions, most individuals can maintain body stability by relying on automatic postural control mechanisms[10]. However, under dual-task conditions, individuals are required to allocate limited cognitive resources to an additional cognitive task while performing postural control. The increased cognitive load often negatively affects balance function[11], and this phenomenon is particularly pronounced in older adults and in individuals with neurological or cardiovascular diseases[12, 13].

With the progression of hypertension and the increase of age, cortical atrophy occurs in the hypertensive population, leading to a decline in dual-task processing

capacity. This is often accompanied by abnormal muscle activation sequences during walking, resulting in gait instability[14] and consequently an elevated risk of falls. Falls can lead to a series of serious consequences in older patients, including fractures of the humerus and hip joint, loss of independence due to fear of falling again, and even permanent disability or death, which severely jeopardize the health and reduce the quality of life of the hypertensive population. Therefore, employing scientific and effective methods to enhance the assessment of balance function in the hypertensive population not only helps identify individuals at high risk of falls but also provides a basis for developing preventive and interventional strategies, which is crucial for reducing fall risk. International studies have reported that approximately 30% of community-dwelling adults aged ≥ 65 years experience at least one fall annually, with hypertension recognized as an important risk factor for falls in older adults[15].

In daily life, individuals frequently encounter situations in which they need to walk and converse simultaneously[16]. The capacity-sharing theory[17] posits that attentional resources are limited; when performing two attention-demanding tasks concurrently, the performance of at least one task deteriorates, implying that cognitive function (i.e., partial diversion of attention) exerts a significant influence on balance function in individuals with hypertension.

Previous studies have primarily focused on dual-task performance in older adults, including outcomes such as the displacement and sway trajectory of the center of gravity, as well as the speed and accuracy of cognitive task completion[18]. Studies on neural inhibition and working memory have demonstrated that older adults exhibit declined cognitive performance under dual-task conditions compared to single-task conditions[19]. Furthermore, working memory research has indicated that increasing cognitive task difficulty (e.g., using a serial subtraction task) facilitates the observation of individual brain activation levels[20]. In addition, significant differences have been observed between older hypertensive individuals and their

healthy counterparts when performing balance tasks on different surface planes[21]. However, there remains a lack of research on the central mechanisms underlying dual-task performance and the state of lower limb muscle activity, specifically, the brain-muscle association mechanisms.

Postural control relies on the coordinated interaction between cortical activity, neuromuscular activation, and biomechanical stability. Functional near-infrared spectroscopy (fNIRS) enables real-time monitoring of cortical activation during standing tasks[22], surface electromyography (sEMG)[23] quantifies lower-limb muscle activation[24], and center of pressure (COP) analysis objectively evaluates postural stability[25]. Together, these complementary measures provide a comprehensive framework for investigating the neural mechanisms underlying postural control.

The aim of this study was to investigate brain-muscle coupling in postural control in individuals with hypertension. Specifically, we examined the effects of altered surface stability and cognitive load on cortical hemodynamics and lower-limb muscle activity under dual-task conditions. We further explored whether brain-muscle coupling metrics could serve as potential biomarkers for identifying balance impairments associated with hypertension.

2. Materials and Methods

2.1 Participants

Sample size was estimated based on a previous fNIRS study on dual-task standing balance in older adults with mild cognitive impairment, which included 21 participants in the MCI group and 19 in the control group, and reported significant between-group differences in prefrontal cortex activation[13]. Using a two-tailed test with $\alpha = 0.05$ and power = 0.80, we determined that a minimum of 18 participants per group would be required. Accounting for a 15% attrition rate due to motion artifacts and poor signal quality, we aimed to enroll at least 20 participants per group. This study initially enrolled 22 patients with hypertension (HT) and 20 healthy controls

(NT). Following data quality control (excluding subjects with excessive signal-to-noise ratios or excessive motion artifacts), 20 subjects from the HT group and 18 from the NT group were ultimately included in the data analysis.

2.2 Inclusion Criteria:

(a) the individuals with hypertension were diagnosed with hypertension by their physicians (a diagnosis of hypertension was performed when systolic blood pressure ≥ 140 mm Hg or diastolic blood pressure ≥ 90 mm Hg) and took antihypertensive drugs daily;

(b) Participants have provided informed consent and voluntarily agreed to participate in this study;

(c) Participants are not taking medications that affect postural stability (e.g., sedatives, hypnotics, gastrointestinal antispasmodics, and tricyclic antidepressants);

(d) Participants are aged ≥ 18 and ≤ 80 years and are right-handed;

(e) Participants are alert and able to cooperate in completing a series of assessments and tests.

2.3 Exclusion criteria:

(a) Inability to stand alone for 10 minutes as required by the experimental protocol;

(b) Presence of acute or chronic diseases, or severe neurological, sensory, or muscular disorders (e.g., diabetes, cervical spondylosis, peripheral neuropathy, vestibular disorders, arthritis, orthopedic conditions, acute infections, malignant tumors, cerebellar disorders, cerebrovascular diseases, delirium, terminal illnesses, psychiatric disorders, severe visual or hearing impairments);

(c) Presence of cognitive impairment (based on MMSE scores: illiterate ≤ 17 points, elementary school education ≤ 20 points, junior high school and above ≤ 24 points) or inability to communicate effectively;

(d) History of hip or knee replacement surgery affecting standing ability;

(e) Pregnant women;

(f) Concurrent participation in other similar research projects.

All participants signed an informed consent form.

2.2 Clinical Assessments

Cognitive function was assessed using the Mini-Mental State Examination (MMSE), a validated 30-point measure of global cognition[26]. Balance confidence was evaluated using the 16-item Activity-Specific Balance Confidence (ABC) Scale (0 – 100%)[27]. Habitual physical activity was assessed using the International Physical Activity Questionnaire (IPAQ), which has demonstrated acceptable reliability and validity in Chinese adults[28]. Anxiety and depressive symptoms were evaluated using the Generalized Anxiety Disorder-7 (GAD-7) and Patient Health Questionnaire-9 (PHQ-9), respectively, both of which have been validated in Chinese populations[29, 30]. After a 20-minute rest period prior to the experiment, participants used an electronic blood pressure monitor with arm cuffs (Model U10K, Omron China) to measure systolic and diastolic blood pressure in both the left and right arms once each, and the average values were calculated.

2.3 fNIRS Data Acquisition and Analysis

A multichannel near-infrared brain functional imaging device (NirSmart, Danyang Huichuang Medical Equipment Co., Ltd., Danyang, Jiangsu, China) was used to record brain activity. fNIRS is an optical method that uses a near-infrared spectral light source probe to noninvasively measure the concentrations of oxyhemoglobin (HbO₂) and deoxyhemoglobin in the cerebral cortex. The system is composed of a near-infrared light source (LED) and an avalanche photodiode as detectors. The light source probe adopts wavelengths of 730 and 850 nm, and the sampling rate is 11 Hz. During the experiment, the participants wore a near-infrared headgear. The experiment used 20 light source probes and 20 detection probes to form 55 effective channels. The average distance between the transmitter and the detector was within 2.7-3.3 cm.

In previous dual-task studies, regions of interest (ROIs) were typically selected from brain areas closely associated with cognitive and balance functions[31]. Accordingly, the regions of interest (ROIs) in this study were defined as follows: the left sensorimotor cortex (ISMC), encompassing channels 32/34/44/45/46/47; the right

sensorimotor cortex (rSMC), encompassing channels 15/37/38/39/54/55; the left premotor cortex (IPMC), encompassing channels 19/33/35/50/51; the right premotor cortex (rPMC), encompassing channels 40/41/42/52/53; the left prefrontal cortex (IPFC), encompassing channels 3/20/22/48/49; and the right prefrontal cortex (rPFC), encompassing channels 11/26/27/31/43. This study primarily utilized central near-infrared functional brain imaging to measure changes in HbO₂ concentration in participants during various standing tasks. HbO₂ is one of the most sensitive and reliable indicators of movement-related hemodynamic changes in the cerebral cortex; compared to deoxyhemoglobin, HbO₂ signals exhibit a greater amplitude of variation and a higher signal-to-noise ratio.

In this study, the NirSpark software package (China Huichuang) was used for fNIRS data processing. First, artifacts unrelated to the experimental data were removed, and a bandpass filter (0.01-0.2 Hz) was applied to filter out physiological noise such as respiration, heartbeat, and low-frequency signal drift. Subsequently, the denoised optical density data were converted into hemoglobin concentration data, and the relative changes in oxygenated hemoglobin (HbO₂) concentration were calculated based on the modified Beer-Lambert law. The “0-30 seconds” time window was defined as the baseline state. Generalized linear models (GLMs) were used to analyze the HbO₂ time-series data. The β values reflect the level of cortical activation in each channel, serving as estimates of the hemodynamic response function (HRF) for the HbO₂ signal and indicating the peak of the HRF function.

2.4 Kinematic Measurements

A force plate (P-6000, BTS bioengineering, Milan, Italy), 60*40 cm, with a sampling frequency of 1,000 Hz was used. It is composed of a pedal, sensor, and base. It provides three-dimensional dynamic data of the X-, Y-, and Z-axes and can display the COP data in real time. Data pre-processing and analysis software were written using MATLAB R2021a (Mathworks, Natick, MA, USA). The raw COP signals were filtered digitally with a 10 Hz low-pass filter (Butterworth). The sway area (mm²), total sway length (mm), mean velocity (mm/s), and amplitude (mm) of the COP in the anterior-posterior (AP) and medial-lateral (ML) directions were measured. Code or

223 formula for calculation of COP (Table 1), for detailed COP parameter explanations,
 224 please see[32].

225 Table 1. Description, code, and formula for calculation of COP.

Variable	Description	Code / formula
Sway area (95% confidenc e ellipse area)	The area of the ellipse which contains the true mean of (X _n , Y _n) 1 ≤ n ≤ N with a probability of 95%	$Area = 2\pi \cdot \frac{N-1}{N-2} \cdot F_{0.95,2,N-2} \cdot \sqrt{RMS_{ML}^2 \cdot RMS_{AP}^2 - COV^2}$
Total sway length	Length of COP trajectory on the base of support	$\sum n \sqrt{(X_{n+1} - X_n)^2 + (Y_{n+1} - Y_n)^2}$
Mean velocity - AP	Determine how fast were the	$\frac{\sum_{n=1}^{N-1} X_{n+1} - X_n }{T}$
Mean velocity - ML	COP displacement s	$\frac{\sum_{n=1}^{N-1} X_{n+1} - X_n }{T}$
Amplitude - AP	Distance between the	max (COP _{AP}) - min (COP _{AP})

Amplitude maximum $\max(\text{COP_ML}) - \min(\text{COP_ML})$
- ML and
 minimum
 COP
 displacement
 for AP and
 ML direction

2.5 Assessment of Lower Limb Muscle Strength

This study utilized the BTS FREEEMG300 wireless surface electromyography (EMG) system. Based on wireless transmission technology, this system establishes a wireless connection between wireless surface electrodes worn by the subject and a computer. The electrodes are portable and feature high accuracy, long-range telemetry, and durability, making them widely applicable in fields such as sports science, clinical diagnosis, rehabilitation assessment, and ergonomics. In this study, the wireless surface EMG system was used primarily to record the root mean square (RMS), average electromyogram (AEMG), and integrated electromyogram (iEMG) of the lower limb muscles. EMG electrode patches were placed on the bilateral tibialis anterior (TA), lateral gastrocnemius (LGS), and rectus femoris (RF) muscles, with specific locations shown in Figures 1A and 1B. EMG parameters were not normalized to maximal voluntary contraction (MVC) due to the practical constraints of the experimental setup. To minimize between-subject variability, electrode placement was standardized across participants following the SENIAM guidelines.

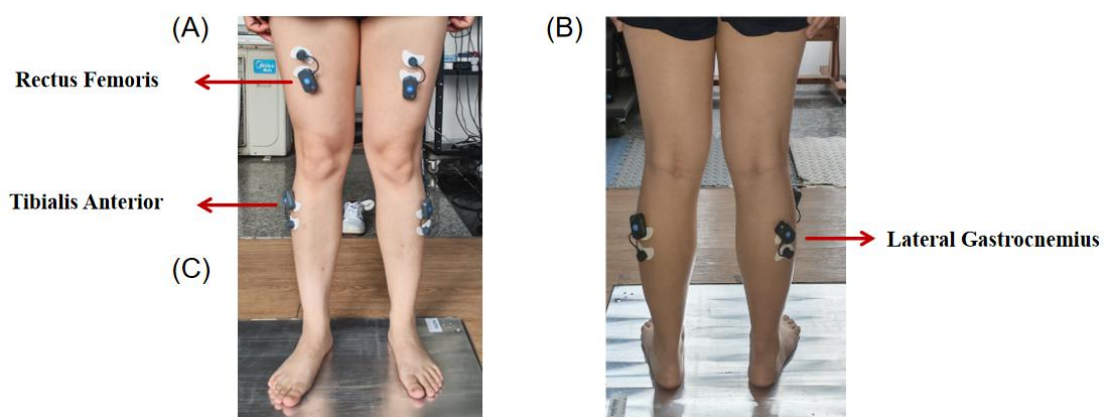


Figure 1. Placement positions of wireless surface electromyography.

2.6 Cognitive Task

During the static standing task, a mental arithmetic task was added to increase cognitive load[33]. Specifically, a random three-digit number greater than 200 was selected, and participants were instructed to subtract 3 from it repeatedly, aiming to complete as many correct subtraction operations as possible within 40 seconds. This task served as a distractor during the standing maintenance process, designed to increase cognitive load.

2.7 Experimental Procedure

This experiment was conducted at the Biomechanics Laboratory of the School of Rehabilitation Medicine, Southern Medical University (Guangzhou, China). A cognitive-motor dual-task standing balance paradigm was employed. The experimental design comprised two factors: visual condition (eyes open vs. eyes closed) and surface stability (stable vs. unstable), yielding four core conditions. These were combined with the presence or absence of a concurrent cognitive task, resulting in six task blocks, each lasting 40 s. The tasks were administered in a fixed order with progressively increasing difficulty to ensure participant safety:

- Task 1 (40 s): Eyes open, stable surface
- Task 2 (40 s): Eyes open, stable surface + serial subtraction by 3
- Task 3 (40 s): Eyes closed, stable surface + serial subtraction by 3
- Task 4 (40 s): Eyes open, unstable surface
- Task 5 (40 s): Eyes open, unstable surface + serial subtraction by 3
- Task 6 (40 s): Eyes closed, unstable surface + serial subtraction by 3

The unstable surface was created using a foam pad (Airex Balance Pad Elite, Switzerland; 50 × 41 × 6 cm), which effectively reduced somatosensory input. For the cognitive task, participants were instructed to count backward by 3s from a randomly assigned three-digit number (e.g., 200) presented at the start of each relevant task; no performance feedback was provided. Prior to formal testing, participants completed a practice session to familiarize themselves with all task

conditions and minimize order effects.

Participants stood barefoot on the force plate in a natural posture, with feet positioned approximately shoulder-width apart, arms relaxed at their sides, and gaze fixed on a visual marker located 1 m ahead at eye level. They were instructed to remain as still as possible and refrain from speaking during each trial. A 60-s baseline period was recorded prior to task initiation, with participants standing quietly on the stable surface with eyes open. Following completion of all six tasks, a 60-s recovery period was recorded under identical baseline conditions. Both baseline and recovery data were used solely for signal stabilization and were excluded from statistical analyses. To prevent falls, a spotter stood nearby during all unstable-surface and eyes-closed conditions.

The standing posture is illustrated in Figures 2C,D, and the task sequence is shown in Figure 2E.

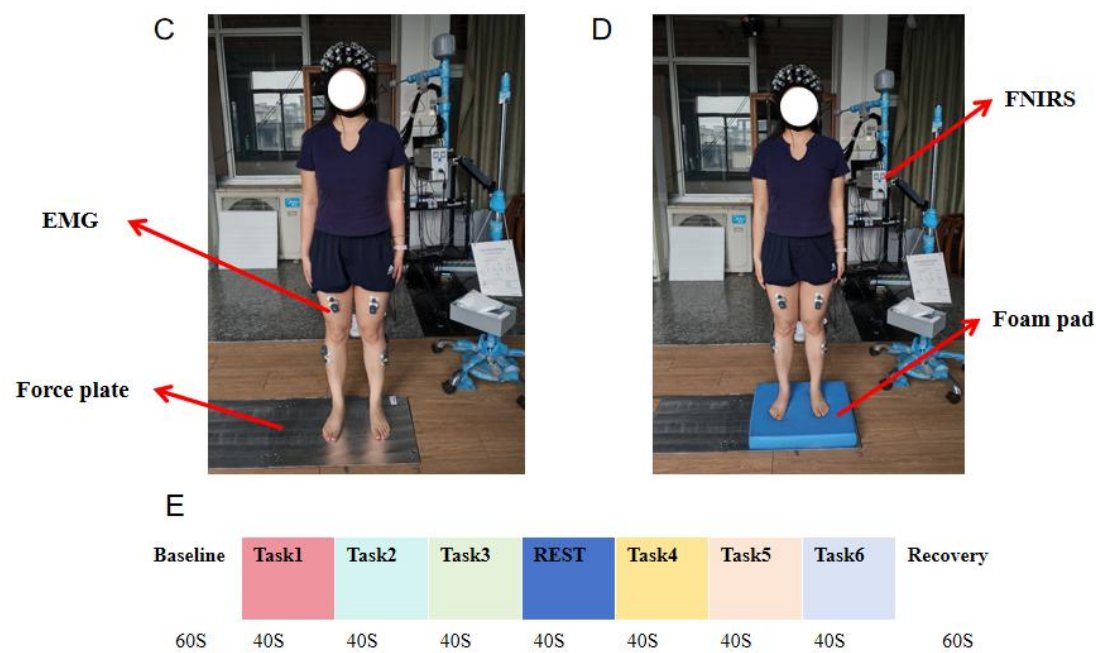


Figure 2. Experimental environment and block design. (C) task1, task 2, and task 3, (D) task 4, task 5, and task 6, (E) study block design.

2.8 Statistical Analysis

Statistical analyses were performed using SPSS version 27.0 (IBM Corp., Armonk, NY, USA). All statistical tests were two-tailed, with the significance level

set at $\alpha = 0.05$. Data normality and homogeneity of variance were assessed using the Shapiro-Wilk and Levene's tests, respectively. Normally distributed continuous variables were presented as mean $\pm$ SD, whereas non-normally distributed variables were presented as median (interquartile range, IQR). Categorical variables were analyzed using the chi-square test or Fisher's exact test, as appropriate. Within-group comparisons between predefined task conditions were performed using paired-samples t-tests for normally distributed data and Wilcoxon signed-rank tests for non-normally distributed data. Between-group comparisons were performed using independent-samples t-tests for normally distributed variables and the Mann-Whitney U test for non-normally distributed variables. Pearson or Spearman correlation analyses were conducted to examine associations between HbO₂ concentrations and COP or EMG parameters. To control for multiple comparisons, the false discovery rate (FDR) method was applied to both pairwise comparisons and correlation analyses. A two-tailed P value < 0.05 was considered statistically significant.

3. Results

3.1 Analysis of Demographic Characteristics and Clinical Measurements Between the NT and HT Groups

This study included a total of 38 participants, comprising 18 in the healthy control group and 20 in the hypertension group. There were no statistically significant differences between the two groups in terms of age, height, weight, heart rate, weekly physical activity, PHQ-9 total score, or balance ability total score (all $P > 0.05$). The hypertension group had significantly higher BMI, systolic blood pressure, diastolic blood pressure, and GAD-7 total scores than the healthy control group (all $P < 0.05$). Among categorical variables, there were statistically significant differences between the two groups in terms of blood pressure stage and medication history (all $P < 0.05$); there were no statistically significant differences in gender, surgical history, comorbidities, or history of falls in the past year (all $P > 0.05$). Overall, the baseline data of the two groups were largely comparable, but the hypertension group exhibited more pronounced intergroup differences in blood pressure-related indicators and anxiety levels, as shown in Table 2.

Table 2. Characteristics of HT and NT (N = 38).

Variable	Category/Level	Normotensive controls (n = 18)	Hypertension (n = 20)	Test statistic	<i>P</i> value
Continuous variables					
Age (years)	—	61.17 ± 12.19	65.65 ± 9.02	-1.297 †	0.203
Height (cm)	—	160.36 ± 7.49	161.70 ± 7.29	-0.558 †	0.580
Body weight (kg)	—	59.64 ± 9.58	64.95 ± 8.09	-1.853 †	0.072
BMI (kg/m ²)	—	23.10 ± 2.61	24.76 ± 1.85	-2.281 †	0.029*
Systolic BP (mmHg)	—	115.56 ± 10.75	124.85 ± 10.63	-2.676 †	0.011*
Diastolic BP (mmHg)	—	74.11 ± 9.71	79.70 ± 7.18	-2.031 †	0.050*
Heart rate (beats/min)	—	73.06 ± 6.45	71.05 ± 10.29	0.710†	0.482
Duration of hypertensio n	—	0.00 ± 0.00	15.00 ± 14.13	-4.497 †	<0.001* *
Physical activity (h/week)	—	6.06 ± 4.54	7.23 ± 6.07	-0.672 †	0.506

Variable	Category/Level	Normotensive controls (n = 18)	Hypertension (n = 20)	Test statistic	<i>P</i> value
GAD-7 total score	—	3.72 ± 2.54	7.40 ± 4.72	-2.944 †	0.006**
PHQ-9 total score	—	8.11 ± 5.06	8.95 ± 4.62	-0.534 †	0.596
Balance ability total score	—	92.13 ± 12.05	89.50 ± 13.03	0.643†	0.524
Categorical variables					
Sex	Male	4 (22.2)	11 (55.0)	2.999‡	0.083
	Female	14 (77.8)	9 (45.0)		
Blood pressure stage	1	4 (22.2)	0 (0.0)	38.000 ‡	<0.001* *
	2	0 (0.0)	17 (85.0)		
	3	0 (0.0)	3 (15.0)		
	4	14 (77.8)	0 (0.0)		
History of surgery	Yes	9 (50.0)	9 (45.0)	0.000‡	1.000
	No	9 (50.0)	11 (55.0)		
Comorbidity	Yes	6 (33.3)	6 (30.0)	0.000‡	1.000

Variable	Category/Level	Normotensive controls (n = 18)	Hypertension (n = 20)	Test statistic	<i>P</i> value
History of medication	No	12 (66.7)	14 (70.0)	13.384 ‡	<0.001* *
	Yes	6 (33.3)	19 (95.0)		
Fall history in past year	No	12 (66.7)	1 (5.0)	0.031‡	0.861
	Yes	4 (22.2)	6 (30.0)		
Education level	No	14 (77.8)	14 (70.0)	2.858‡	0.414
	Primary school or below	4 (22.2)	2 (10.0)		
	Junior high school	1 (5.6)	3 (15.0)		
	Senior high school	6 (33.3)	4 (20.0)		
Smoking history	College or above	7 (38.9)	11 (55.0)	8.003‡	0.018*
	Never	17 (94.4)	11 (55.0)		
	Former	0 (0.0)	5 (25.0)		
Drinking history	Current	1 (5.6)	4 (20.0)	4.122‡	0.127
	Never	15 (83.3)	11 (55.0)		
	Occasional	2 (11.1)	8 (40.0)		

Variable	Category/Level	Normotensive controls (n = 18)	Hypertension (n = 20)	Test statistic	<i>P</i> value
	Frequent	1 (5.6)	1 (5.0)		

Continuous variables are expressed as mean $\pm$ standard deviation, and categorical variables are expressed as n (%). BMI: Body Mass Index; MMSE: Mini-Mental State Examination; ABC: Activity-Specific Balance Confidence Scale; PHQ-9: Patient Health Questionnaire-9; GAD-7: Generalized Anxiety Disorder Scale-7; $\dagger$ Independent-samples t statistics are reported for continuous variables. $\ddagger$ χ^2 statistics are reported for categorical variables. * $p < 0.05$, ** $p < 0.01$.

3.2 Analysis the activation of HbO2 across groups during Tasks 1-6

There were no significant differences in HbO2 activation between the two groups across all tasks and brain regions ($p > 0.05$), as shown in Figure 3.

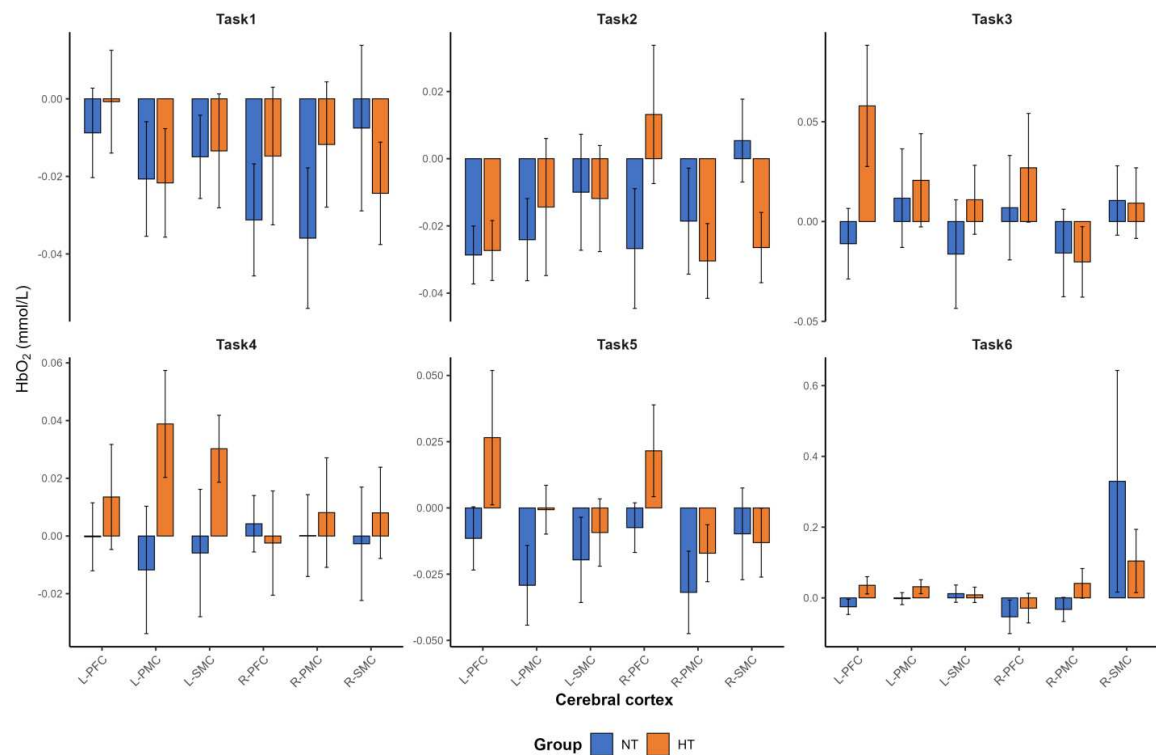


Figure 3. Analysis of HbO2 concentration difference across groups during Tasks 1-6.

NT, normotension group; HT, hypertension group. lSMC, left sensorimotor cortex; rSMC, right sensorimotor cortex; lPMC, left premotor cortex; rPMC, right premotor cortex; lPFC, left prefrontal cortex; rPFC, right prefrontal cortex.

3.3 Intragroup analysis of HbO2 results

Significant differences within the HT group are as follows: lSMC activation was higher in Task 4 than in Task 1 and Task 5 ($p < 0.05$); rSMC activation was higher in Task 6 than in Task 5 ($p < 0.05$); activation in lPMC was higher in Task 4 than in Task 1 ($p < 0.01$) and higher in Task 3 than in Task 2 ($p < 0.05$); activation in lPFC was higher in Task 3 than in Task 2 ($p < 0.01$) and higher in Task 5 than in Task 2 ($p < 0.05$). Within the HT group, there were no significant differences in activation between rSMC, rPMC, and rPFC across all task comparisons ($p > 0.05$), as shown in Figure 4(a). Within the NT group, there were no significant differences in activation across all brain regions in any task comparisons ($p > 0.05$), as shown in Figure 4(b).

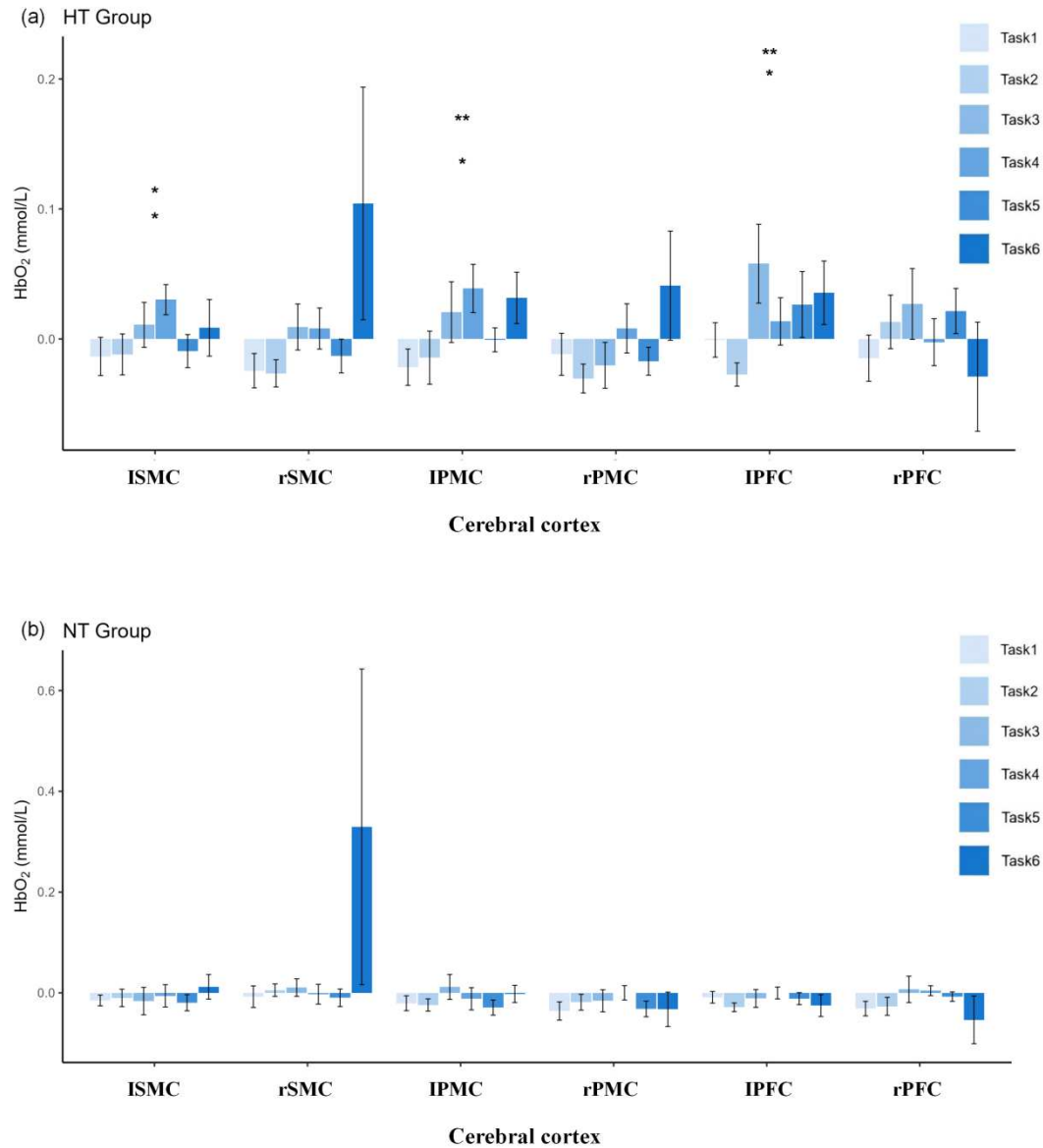


Figure 4. Intragroup analysis of HbO₂ concentration across task conditions. (a) HT group; (b) NT group. * $p < .05$, ** $p < .01$. ISMC, left sensorimotor cortex; rSMC, right sensorimotor cortex; IPMC, left premotor cortex; rPMC, right premotor cortex; IPFC, left prefrontal cortex; rPFC, right prefrontal cortex.

3.4 Analysis of COP parameters across groups during Tasks 1-6

In Task 2, the swing area ($p = 0.047$) and amplitude in the ML direction ($p = 0.018$) were both significantly greater in the NT group than in the HT group. In Tasks 1, 3, 4, 5, and 6, no significant between-group differences were observed for any COP parameters (all $p > 0.05$). It is worth noting that, although not statistically significant,

the HT group exhibited greater variability in sway area than the NT group in Tasks 4, 5, and 6, supporting a potential trend toward reduced postural stability in the HT group under more challenging task conditions, as shown in Figure 5.

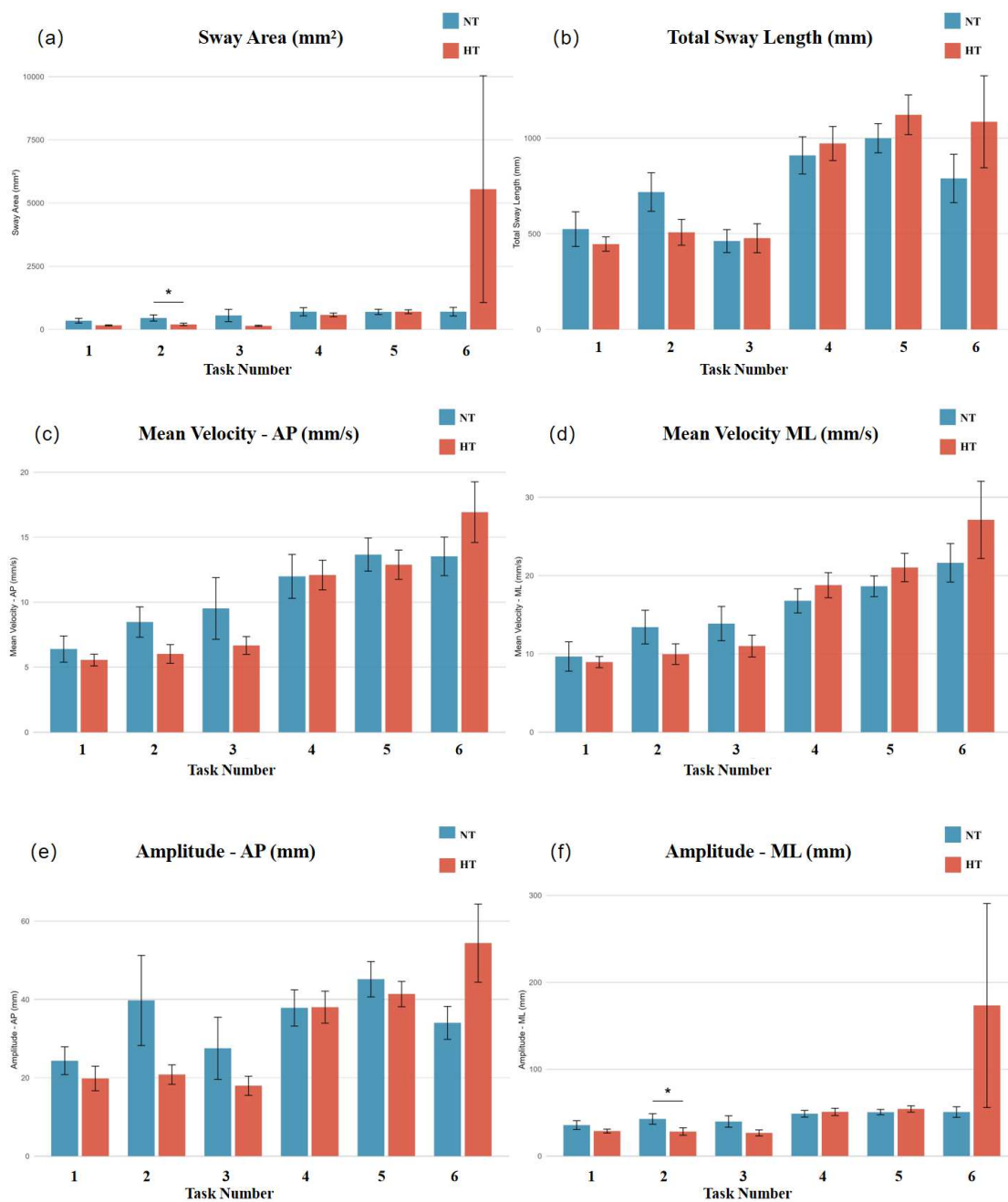
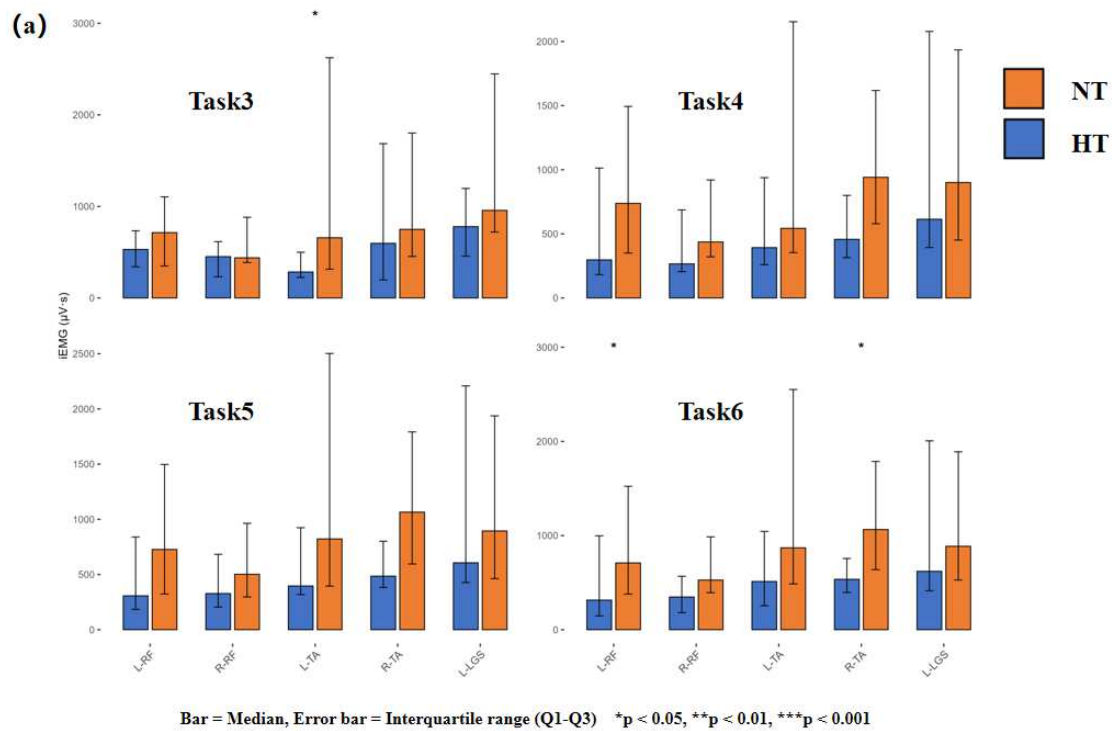


Figure 5. Between-group comparison of COP parameters across Tasks 1-6: (a) sway area (mm²), (b) total sway length (mm), (c) mean velocity in the AP direction (mm/s), (d) mean velocity in the ML direction (mm/s), (e) amplitude in the AP direction (mm), and (f) amplitude in the ML direction (mm). * $p < .05$. NT, neurotypical group; HT, hypertension group; AP, anterior-posterior; ML, medial-lateral.

3.5 Analysis of lower limb EMG parameters across groups during Tasks 1-6

Compared with the NT group, the HT group showed significantly higher RMS, AEMG, and iEMG values for the L-RF and R-TA in Tasks 5 and 6 ($p < 0.05$), significantly higher AEMG for the R-TA in Task 4 ($p = 0.050$), and significantly higher iEMG for the L-TA in Task 3 ($p = 0.034$). No significant differences were observed between groups for the remaining tasks or muscle parameters (all $p > 0.05$), indicating that patients with hypertension require greater lower limb muscle activation to maintain postural stability during more challenging balance conditions, as shown in Figure 6a–c.



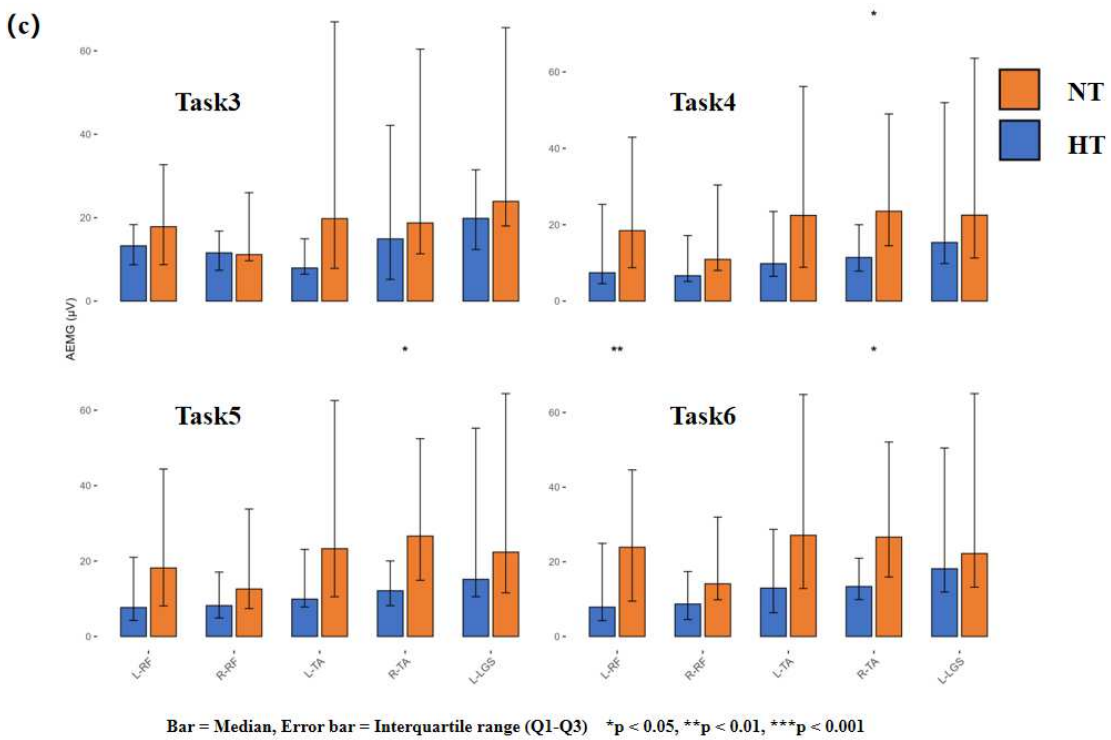
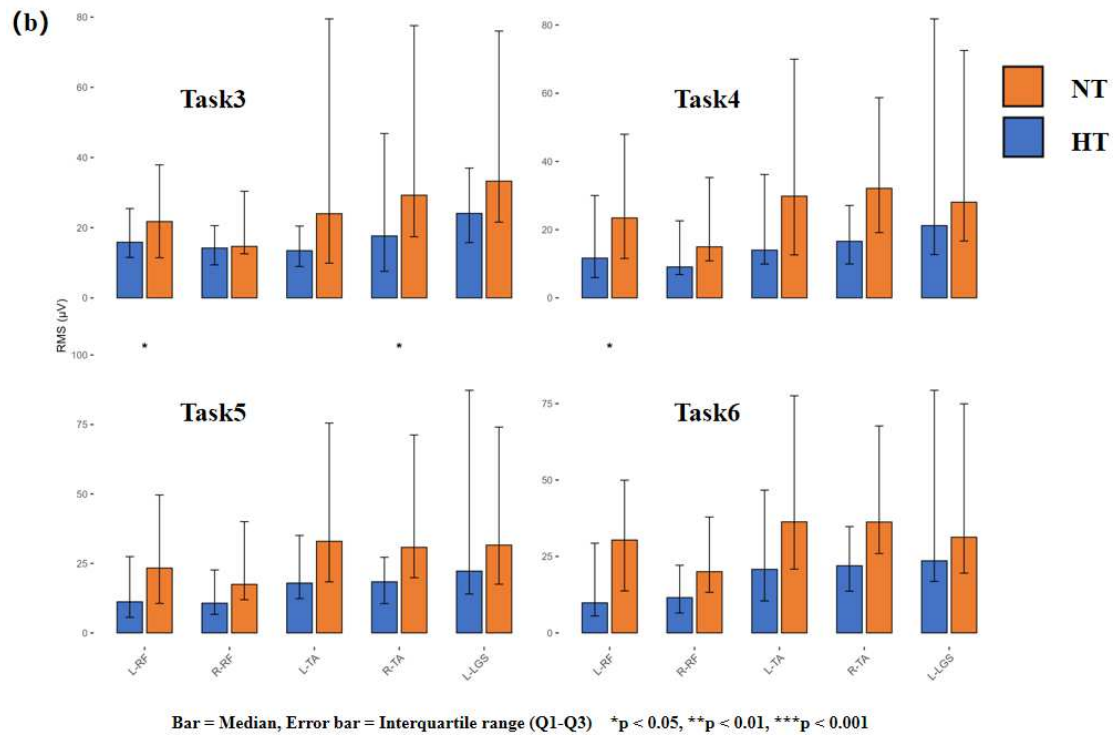


Figure 6. Between-group comparisons of lower limb muscle iEMG, RMS and AEMG during Tasks 3-6.

3.6 Correlation Analysis of HbO₂, COP Pressure Centers, and Surface Electromyography Between the Two Groups

We used correlation analysis to examine the relationships between HbO₂

activation and COP parameters, as well as wireless surface electromyography (EMG) measures, in the NT group and the HT group during Tasks 1-6.

In the NT group, during Task 1, ISMC activation was significantly positively correlated with L-RF muscle activity (RMS, AEMG, and iEMG) ($r = 0.61-0.63$, all $p < 0.01$), and IPFC activation was also significantly positively correlated with L-RF muscle activity ($r = 0.58-0.62$, all $p < 0.05$). During Task 2, ISMC activation was significantly negatively correlated with the COP swing area ($r = -0.48$, $p = 0.045$), mean velocity in the AP direction ($r = -0.53$, $p = 0.024$), and amplitude in the AP direction ($r = -0.56$, $p = 0.018$). During Tasks 3 and 4, rPMC activation was positively correlated with L-RF RMS ($r \approx 0.49$, $p < 0.05$). During Tasks 4 and 5, ISMC activation was negatively correlated with COP swing area ($r = -0.56$ and -0.47 , both $p < 0.05$). During Task 6, rPMC activation was negatively correlated with L-RF AEMG and iEMG ($r \approx -0.48$, $p < 0.05$). As shown in Figure 7(a).

In the HT group, IPMC activation showed a consistently significant positive correlation with L-RF muscle activity (RMS, AEMG, and iEMG) during Tasks 1, 2, and 4 ($r = 0.46-0.64$, all $p < 0.05$). During Task 1, rPMC and IPFC activation were also positively correlated with L-RF AEMG and iEMG ($r = 0.48-0.52$, all $p < 0.05$). During Task 3, ISMC activation was strongly positively correlated with L-RF RMS, AEMG, and iEMG ($r = 0.63$, all $p < 0.01$). In the HT group, no significant correlation was found between HbO₂ and COP parameters under any task conditions (all $p > 0.05$). As shown in Figure 7(b).

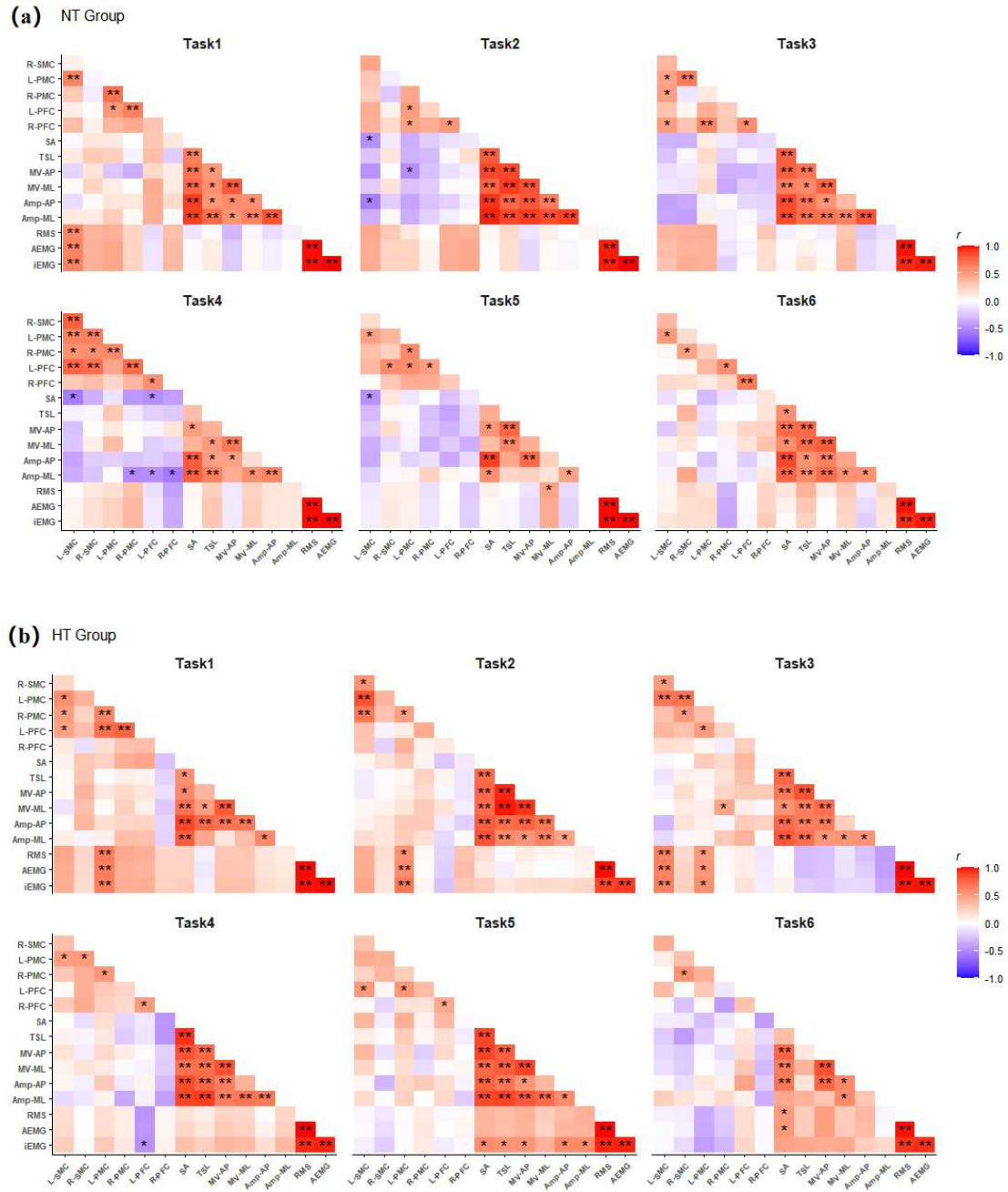


Figure 7. Correlation heatmaps between HbO₂, COP, and EMG parameters in the HT and NT groups across Tasks 1-6. Color scale: Spearman's r (blue to red). Asterisks indicate significance (* $P < 0.05$, ** $P < 0.01$). Empty cells = non-significant. Abbreviations: SMC, sensorimotor cortex; PMC, premotor cortex; PFC, prefrontal cortex; SA, sway area; TSA, total sway length; MV, mean velocity; Amp, amplitude; AP/ML, anteroposterior/mediolateral; RMS, root mean square; AEMG, average EMG; iEMG, integrated EMG.

4. Discussion

This study employed fNIRS, COP, and wireless surface electromyography (EMG) to compare cortical activation, balance function, and lower limb muscle activity between a hypertensive group (HT) and a healthy control group (NT) during postural-cognitive tasks of varying difficulty, and to investigate brain-body association characteristics. The results showed no significant between-group differences in HbO₂ activation levels across all tasks and brain regions; however, hypertension changes the brain-body strategy during challenging postural control. HT showed a trend toward greater postural sway during Tasks 4-6, although between-group differences did not reach statistical significance. In the complex balance tasks, the HT group exhibited significantly higher RMS, AEMG, and iEMG values in lower limb muscles (L-RF, R-TA) compared to the NT group, indicating enhanced compensatory muscle activation. Correlation analysis indicated distinct patterns of brain-body associations between the two groups. Specifically, cortical activation was predominantly associated with COP parameters in the NT group, whereas cortical activation was more closely associated with lower-limb EMG activity in the HT group. These findings may suggest that the two groups relied on different brain-body control mechanisms during complex balance tasks.

4.1 Cortical activation patterns and compensatory trends in the HT group

This study found no significant differences in HbO₂ activation between the two groups across all tasks and brain regions, implying that between-group differences in task-related cortical activation may be small in patients with mild hypertension. Despite the absence of significant between-group differences, within-group analysis revealed distinct patterns of cortical activation in the HT group. Specifically, ISMC activation was higher in Task 4 than in Task 1 and Task 5; IPMC activation was higher in Task 4 than in Task 1 and higher in Task 3 than in Task 2; and IPFC activation was higher in Task 3 than in Task 2 and higher in Task 5 than in Task 2. In contrast, the NT group exhibited no significant differences across any task or brain region. This pattern suggests that the HT group required additional sensorimotor and

prefrontal cortical resources to maintain postural stability under challenging conditions (unstable surface, visual constraint, and concurrent cognitive load).

These findings are consistent with the "compensatory resource mobilization" framework. St George et al. demonstrated[29] that older adults compensate for sensorimotor deficits by increasing PFC activation during balance tasks. Similarly, A study reportedthat PFC activation shifts from unilateral to bilateral patterns in older adults performing dual-task walking, supporting recruitment of additional cognitive resources[25]. A systematic review and meta-analysis further confirmed an association between cerebral small vessel disease severity and reduced neurovascular coupling[28], providing a potential neural mechanism for the increased cortical activation observed in the HT group. However, given the exploratory nature of this study, these findings warrant validation in future studies with larger sample sizes.

4.2 A trend toward impaired postural control in the HT group during challenging tasks

In Task 6, the HT group showed substantially larger sway area, total sway length, and ML amplitude than the NT group. Although these differences did not reach statistical significance, the magnitude of the observed changes suggests a possible deterioration in postural stability under highly challenging conditions. It is worth noting that in Tasks 2, the total swing length and ML amplitude in the HT group were already significantly lower than those in the NT group, supporting that these two measures are more sensitive to early impairments in postural control. A study by Matsuda et al. noted that older adults exhibit significantly increased postural sway amplitude under conditions of instability and distraction, accompanied by changes in postural control strategies[34]. Furthermore, Kang and Lipsitz found that under dual-task conditions, older adults exhibited increased physiological sway amplitude and reduced stiffness, indicating that cognitive load diverted attentional resources required for postural control[35].

Possible mechanisms by which hypertension leads to impaired postural control

include the following: First, long-term hypertension can damage the structure and function of the brainstem, cerebellum, and basal ganglia, thereby affecting sensorimotor integration. Ungvari et al.[36]systematically described how hypertension-induced structural damage and functional disorders in cerebral microcirculation can lead to cognitive and motor impairments. Second, impaired cerebral autoregulation results in an insufficient increase in task-induced cerebral blood flow. Furthermore, hypertension may also be associated with peripheral neuropathy and reduced muscle function. You et al.[37]found that patients with white matter lesions (a common radiological finding in individuals with hypertension) exhibited significantly impaired balance, and that training with the Pro-kin system effectively improved their balance function. In this study, changes in the COP parameters observed in the HT group during Tasks 4 through 6 suggest that, under tasks of moderate difficulty, patients with hypertension are still able to maintain postural stability with some difficulty. These findings may indicate that compensatory mechanisms become progressively less effective as postural task demands increase.

4.3 Increased compensatory activation of lower limb muscles in the HT group during postural-cognitive challenges

EMG analysis revealed that in Tasks 5 and 6, the HT group exhibited significantly higher RMS, AEMG, and iEMG values for the L-RF and R-TA than the NT group, which may reflect increased muscular recruitment to maintain postural stability during challenging tasks. The L-RF, acting as a hip flexor and knee extensor, contributes to lower-limb support and postural stabilization, whereas the R-TA plays an important role in ankle dorsiflexion and postural adjustments. Previous studies have similarly reported increased lower-limb muscle activation and co-activation during challenging balance tasks in older adults, accompanied by reduced corticomuscular coherence and greater attentional demand[38]. Our findings are generally consistent with these observations, indicating a shift toward a muscle-driven compensatory strategy under increased postural demands. Furthermore, aging-related

adaptations in postural control have been associated with reorganization of intermuscular coordination^[33], characterized by altered muscle coupling and increased low-frequency coherence, which may reflect reduced efficiency of central postural control networks^[34]. However, because EMG amplitudes were not normalized to maximal voluntary contraction (MVC), these findings should be interpreted cautiously and primarily reflect relative between-group differences under standardized testing conditions rather than absolute differences in muscle activation. The increased EMG activity may therefore represent a peripheral manifestation of compensatory cortical recruitment.

4.4 The two groups exhibited different brain-body association patterns: the NT group showed cortical-COP association, while the HT group showed cortical-EMG association

Correlation analysis in this study revealed that cortical activation in the NT group was primarily associated with COP parameters, whereas cortical activation in the HT group was primarily associated with EMG parameters. These findings provide a new perspective for understanding the neural compensation mechanisms in patients with hypertension.

In the NT group, the negative correlation between ISMC and COP parameters ($r = -0.48$ to -0.56) indicates that higher activation in the sensorimotor cortex is associated with smaller postural sway. This pattern may reflect efficient sensorimotor integration during postural control in healthy individuals. Cortico-muscular coherence (CMC) analysis has been used to quantify functional connectivity between the motor cortex and muscles[39]. A study recently found significant alterations in both afferent and efferent CMC during standing postural control in amputees, implying that differences in sensory feedback processing are key factors influencing brain-body association[40]. In contrast to the NT group, no significant correlations between cortical activity and COP were found in the HT group. The positive correlation

between IPMC and L-RF electromyographic activity ($r = 0.46-0.64$) suggests that higher activation of the premotor cortex is associated with stronger lower limb muscle activity; however, this increased muscle activation did not effectively improve postural control. This pattern may reflect reduced efficiency in neural resource utilization and greater reliance on peripheral muscular compensation. Similarly, a systematic review on postural control in patients with Parkinson's disease also noted that cortical involvement in postural control to compensate for damage to subcortical structures is a common pattern of neural reorganization[41].

5. Clinical Implications

The findings of this study have important implications for the clinical assessment and rehabilitation of individuals with hypertension. COP parameters, particularly sway area and mediolateral (ML) sway amplitude, may serve as sensitive behavioral markers of early postural impairment. Even in patients with normal cognitive screening results, abnormal COP performance may indicate underlying neuromotor dysfunction that is not readily detected by conventional clinical assessments. Lehmann et al. demonstrated that balance training significantly reduced postural sway while decreasing excessive prefrontal cortex activation in older adults, suggesting that cortical efficiency can be improved through rehabilitation[42].

Our findings further support the value of multimodal assessment combining cortical activation, COP, and EMG to facilitate the early identification of hypertension-related neuromotor dysfunction. Enhanced corticomuscular coupling may represent a potential biomarker of compensatory neuromotor adaptation, although further validation is required. Consistent with this perspective, Rubega et al. reported that combined EEG-EMG recordings provide valuable information on cortical and muscular activity during balance tasks, while emphasizing the need for standardized acquisition protocols and analytical methods[38]. Given the coexistence of impaired balance, increased muscular compensation, and altered brain-muscle coupling observed in the HT group, rehabilitation strategies should integrate balance,

cognitive, and muscle-strengthening training rather than targeting a single functional domain. This multidomain approach is supported by a recent systematic review, which demonstrated that functional training combining physical exercise with cognitive challenges improves activities of daily living and cognitive function in community-dwelling older adults, particularly among those with mild cognitive impairment[43]. Furthermore, Yang and Webb proposed that impaired neurovascular coupling is a clinically accessible biomarker of hypertension-related cerebral dysfunction, highlighting the potential of multimodal neurophysiological assessment for the early detection and personalized rehabilitation of hypertension-related neuromotor dysfunction[18].

6. Limitations and Future Directions

This study has the following limitations. First, the sample size was relatively small, and all participants in the HT group had mild hypertension (Stage 1); therefore, the results may not be applicable to individuals with moderate-to-severe hypertension. Second, cognitive task performance (accuracy and response rate) was not recorded during the mental arithmetic tasks, precluding verification that both groups experienced comparable cognitive loads under the dual-task conditions. Third, this study did not collect information on the type, dosage, or duration of antihypertensive medication use, making it impossible to rule out the potential influence of medication on the results. Fourth, EMG amplitudes were not normalized to maximal voluntary contraction (MVC). Although electrode placement and data acquisition procedures were standardized across participants, between-subject comparisons of absolute EMG values should be interpreted with caution, as signal amplitudes may be influenced by factors such as subcutaneous tissue thickness, skin impedance, and individual muscle characteristics.

Future studies should address the following areas for improvement. First, the sample size should be expanded to include patients with varying degrees of hypertension, and detailed medication information should be collected. Second,

cognitive task performance should be systematically recorded in future dual-task paradigms to enable manipulation checks and to quantify the relationship between cognitive engagement and postural outcomes. Third, future studies should incorporate standardized EMG normalization procedures, such as MVC or other reference contractions, to improve the reliability and comparability of muscle activation measurements. Furthermore, longitudinal studies are warranted to clarify the causal mechanisms underlying hypertension-related alterations in brain-body associations.

7. Conclusion

This study found that the two groups of participants exhibited distinct brain-body association patterns: the NT group predominantly showed cortical activation associated with COP parameters, whereas the HT group predominantly showed cortical activation associated with lower-limb EMG activity, meaning that activation in the premotor cortex was positively correlated with electromyographic activity. These findings raise the possibility that hypertension is associated with a shift from a predominantly cortical-postural coupling pattern toward greater cortical-muscular coupling during challenging postural control.

8. Declarations

Ethics approval and consent to participate

This study was approved by the Medical Research Ethics Committee of Zhujiang Hospital, Southern Medical University in April 2025 (Approval No.: 2025-KY-085-02) and registered with the China Clinical Trials Registry (Registration No.: ChiCTR2600116874) on January 15, 2026. Written informed consent was obtained from all participants prior to their involvement in the study.

Consent for publication

Not applicable. This manuscript does not contain any individual person's data in any form (including individual details, images, or videos).

Availability of data and materials

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

QZ, GH, HL and NC designed the study. QW and YC drafted the manuscript, recruited participants, and analyzed the data. BQ was responsible for random assignment, intervention training, and participant recruitment. QR drafted the manuscript and recruited participants. HM was responsible for intervention training and participant recruitment. SL, MH and YM collected the data. XS contributed to data interpretation. HL also contributed to participant recruitment. All authors reviewed and approved the final version of the manuscript. QZ, GH, HL and NC are corresponding authors and contributed equally to this work.

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