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# Effects of Aquatic Cognitive-Motor Exercise on Balance Performance and Task-Dependent Neural Activity in Older Adults with Mild Cognitive Impairment: A Pilot Study

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# Effects of Aquatic Cognitive-Motor Exercise on Balance Performance and Task-Dependent Neural Activity in Older Adults with Mild Cognitive Impairment: A Pilot Study

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## ABSTRACT

**Objective:**To investigate the effects of an 8-week aquatic cognitive-motor exercise (ACME) program compared with an aquatic high-intensity interval training (AHIIT) program of equivalent intensity on postural control, task-dependent cortical activity, functional fitness, and cognitive function in older adults with mild cognitive impairment (MCI).

**Methods:**Thirty older adults with MCI were randomly assigned to ACME or AHIIT groups. Both groups completed aquatic training twice weekly for 8 weeks (60 min/session), with exercise intensity progressively increased from 70% to 90% of maximum heart rate. The ACME group performed concurrent cognitive tasks during exercise, whereas the AHIIT group completed identical exercises without cognitive loading. Twenty-two participants completed the intervention (ACME: n = 10; AHIIT: n = 12). Postural control was assessed using a three-dimensional force plate during parallel and single-leg stances, with simultaneous functional near-infrared spectroscopy (fNIRS) recording of task-dependent cortical activity. Cognitive function and functional performance were assessed using the Montreal Cognitive Assessment (MoCA), Timed Up and Go (TUG), Y-Balance Test (YBT), and 30-second Chair Stand Test.

**Results:**Both groups showed significant improvements in cognitive function after training, with no significant Group × Time interaction. Postural sway during parallel stance was reduced over time in both groups. Compared with AHIIT, ACME

produced greater improvements in left single-leg sway velocity, maximum anteroposterior and mediolateral sway amplitudes, and left-leg YBT performance. No significant between-group differences were observed for right single-leg sway or TUG performance. fNIRS analysis revealed a significant Group × Time interaction in the frontopolar region during parallel stance, with increased HbO response after ACME but decreased response after AHIIT. Exploratory analyses indicated greater task-dependent HbO modulation following ACME, particularly within prefrontal cognitive-control regions.

**Conclusion:**Both aquatic exercise programs improved postural stability and cognitive function in older adults with MCI. Compared with intensity-matched AHIIT, ACME induced greater improvements in dynamic balance performance and distinct frontopolar cortical adaptations. These findings suggest that integrating cognitive loading into aquatic exercise may enhance balance-related neural adaptations and represents a feasible rehabilitation strategy for individuals with MCI.

Trial registration: Chinese Clinical Trial Registry (ChiCTR), ChiCTR2600136888. Registered 16 November 2026. Retrospectively registered.

**Keywords:** Mild cognitive impairment; Aquatic cognitive-motor exercise; Aquatic high-intensity interval training; Postural control; Neuroplasticity

## INTRODUCTION

Mild cognitive impairment (MCI) is a common prodromal neurodegenerative condition in older adults that markedly increases the risk of progression to dementia[1].

It is frequently accompanied by impaired balance control[2], limitations in activities of daily living[3], and disturbances in cerebral blood flow regulation[4,5]. Hemodynamic abnormalities and executive function decline represent core pathophysiological mechanisms underlying MCI[4,6]. Older adults with MCI commonly exhibit reduced cerebral oxygenation[5,6], compromised postural control[2], and lower scores on standardized cognitive assessments such as the Mini-Mental State Examination (MMSE) and Montreal Cognitive Assessment (MoCA). Vascular dysfunction can lead to insufficient microvascular perfusion in the brain, thereby exacerbating the interrelated deterioration of cognitive and motor functions[4,6]. In turn, declining balance ability further elevates fall risk, establishing a vicious cycle[2,7]. Although cognitive impairment is generally progressive and difficult to reverse, targeted interventions can substantially delay cognitive decline in older populations. Exercise, in particular, has been shown to slow cognitive deterioration through multiple biological mechanisms and to promote the reorganization and optimization of brain functional networks[8].

Dual-task cognitive-motor training has emerged as one of the most effective non-pharmacological interventions for mitigating cognitive and functional decline associated with MCI. It simultaneously activates motor and cognitive neural networks, thereby enhancing attentional allocation, postural control, and balance performance in older adults[9,10]. Because cognitive and motor demands frequently occur concurrently in daily life, this training approach closely mirrors real-world functional requirements. It also offers the advantages of minimal side effects, low cost, and strong potential for

sustained patient engagement[11]. Separately, high-intensity interval training (HIIT), through intermittent high-intensity stimuli, can effectively increase blood flow velocity and oxygenation levels in the prefrontal cortex and motor cortical areas, thereby contributing to improvements in balance control[12].

Previous studies have predominantly employed land-based exercise interventions, which are widely recommended for improving cognitive function, physical fitness, and activities of daily living in older adults. However, their effects on cerebral hemodynamics and dual-task coordination are often limited[13]. In particular, when cognitive processing and postural control are required simultaneously, some older adults—especially those with mild cognitive impairment—may continue to exhibit inefficient attentional allocation, reduced postural stability, and increased dual-task costs[14]. Meanwhile, land-based exercise requires individuals to continuously counteract gravity and tolerate ground-reaction forces, potentially increasing mechanical loading on the lower-extremity joints and musculoskeletal system. Among older adults with degenerative joint conditions, muscle weakness, gait instability, or impaired balance, such training may induce pain, fatigue, or discomfort and may also increase exposure to falls and fall-related injuries[15,16]. Concerns about falling may further reduce willingness to participate in exercise and compromise adherence. Consequently, frail older adults and those with poor balance may find it difficult to engage in land-based training safely and consistently over the long term, thereby limiting the extent of intervention benefits and the broader implementation of these programs in vulnerable older populations[16,17].

Aquatic exercise represents an innovative exercise modality that offers a promising solution to these limitations. The aquatic environment utilizes buoyancy, hydrostatic pressure, and water resistance to simultaneously reduce joint stress, prolong balance reaction time, and alleviate fear of falling[18]. As a highly suitable training mode for older adults, aquatic exercise has demonstrated unique hydrodynamic properties that significantly enhance physical fitness and cerebral blood flow-related indices, frequently outperforming land-based exercise[19,20]. Water immersion of the chest and lower body generates external pressure that promotes systemic circulation and augments cerebral blood flow[21]. At equivalent intensities, aquatic exercise elicits greater increases in cerebral oxygenation than land-based exercise[19] and may more effectively improve episodic memory in older adults[22]. Aquatic HIIT can markedly elevate cerebral oxygenation and oxygenation efficiency through intermittent high-intensity stimuli[19,23], whereas aquatic dual-task training facilitates safe multisensory integration, thereby strengthening cognitive-motor coupling and ultimately enhancing balance function via improved cerebral hemodynamics[9,11].

Therefore, the primary aim of this pilot study was to compare the effects of an 8-week aquatic high-intensity interval training (AHIIT) versus an aquatic cognitive-motor exercise (ACME) program on cerebral hemodynamics, balance ability, functional fitness, and cognitive function in older adults with mild cognitive impairment (MCI). As these two aquatic exercise modalities have not yet been directly compared head-to-head in the MCI population, the present study incorporated cerebral oxygenation and postural control measures as primary outcomes. We hypothesized that

both aquatic interventions would improve cerebral hemodynamics, balance performance, functional fitness, and cognitive function with ACME demonstrating superior benefits in enhancing prefrontal cortical activation and promoting corresponding improvements in balance performance.

## METHODS

### Participants

Thirty older adults with MCI, aged 60–75 years, were recruited for this study. Participants were screened and confirmed to have MCI using MoCA[24]. After providing their written informed consent, all participants reported being free from any cardiorespiratory or neurological pathology (other than MCI), and had not experienced any orthopedic fracture or undergone any surgical intervention to the lower extremities in the 6 months prior to the study. Additionally, none of the participants were taking any medications known to affect their balance, cognition, or cardiovascular function.

### Study Design

A parallel two-group randomized controlled trial design was implemented in accordance with the Consolidated Standards for Reporting of Trials (CONSORT) guidelines[25]. This study was a randomized controlled trial. Participants were allocated to the intervention groups using a computer-generated random sequence. They were blinded to the study hypotheses, were not informed which intervention was expected to be more effective, and were unaware of the intervention administered to the other group. All study procedures were approved by the Institutional Review Board of

Wuhan Sports University (2025164). This trial was retrospectively registered in the Chinese Clinical Trial Registry (ChiCTR, ChiCTR2600136888) on 16 November 2026, as completion of the registration process was delayed after the first participant was enrolled. All participants completed baseline assessments, including MoCA, Timed Up-and-Go (TUG) test, Y-Balance Test (YBT), 30-Second Chair Stand Test (30-s CST), double- and single-leg sway assessments, and functional near-infrared spectroscope (fNIRS) measurements. After the 8-week intervention, 12 participants in the Aquatic HIIT group and 10 participants in the Aquatic Cognitive-Motor Exercise group completed the post-intervention assessments using the same outcome measures; participants who attended an insufficient number of intervention sessions were excluded. (Figure 1).

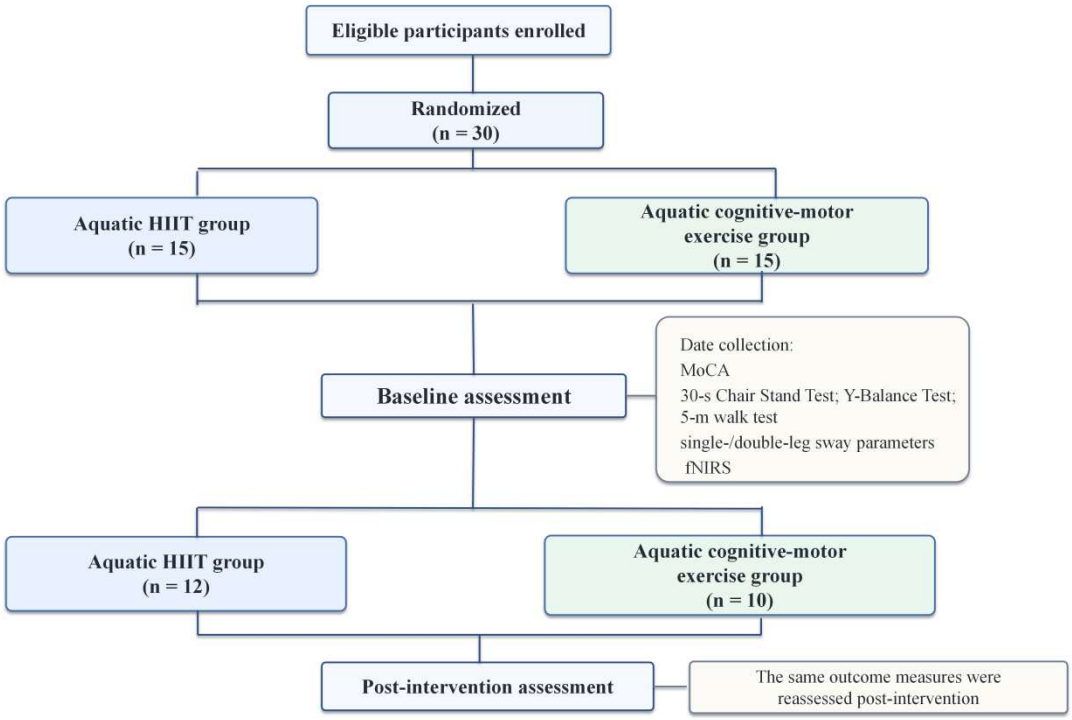


**Figure 1 Participant flow and study design**

## Experimental Procedures

Participants completed screening and familiarization procedures before signing the informed consent form. The baseline assessment protocol served as the reference procedure for all subsequent evaluations. The MoCA cutoff score for possible MCI was set below 26 points (or ≤25/≤24 after adjustment for education)[24]. Eligible participants performed a familiarization session in the pool one week prior to the intervention. Baseline assessments comprised both functional clinical tests and instrumented laboratory tests. Functional clinical tests included the TUG[26], YBT[27], and 30-s CST[28]. Instrumented laboratory tests involved bipedal and unipedal stance assessments on a force plate with simultaneous fNIRS recording of prefrontal cortical activity. All baseline assessments were repeated after the 8-week intervention using identical protocols (Figure 2).

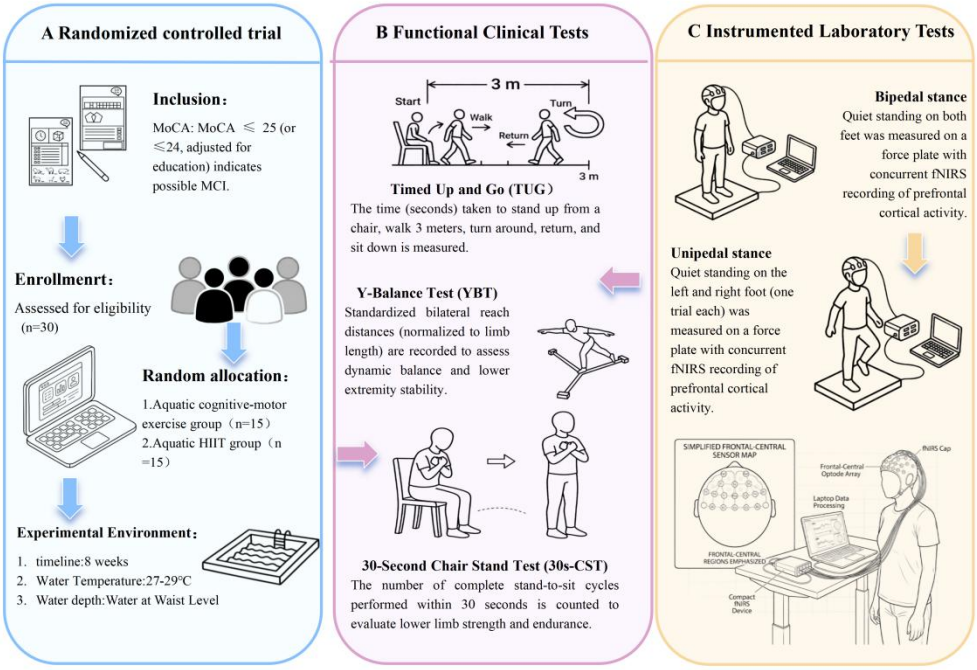


**Figure 2. Study design and outcome assessment procedures**

## Interventions

The intervention program consisted of an 8-week aquatic exercise training conducted twice per week in a sports club pool. The program was structured into three progressive phases over 8 weeks: Phase I (Weeks 1–3) at 70% maximum heart rate (HRmax), Phase II (Weeks 4–6) at 80% HRmax, and Phase III (Weeks 7–8) at 90% HRmax. HRmax was estimated using formula 220 – age[26]. Sessions were held in a sports club pool with water depth ranging from 1.2 to 1.8 m and water temperature maintained at approximately 27–29°C. Participants attended two sessions per week (16 sessions in total), with each lasting 60 minutes including warm-up, main exercise component,, cognitive-motor activity (ACME only), and cool-down. All sessions were supervised by an experienced aquatic fitness instructor.

### Aquatic Cognitive-Motor Exercise Group

The ACME program consisted of 60-minute sessions combining high-intensity aquatic exercises with simultaneous cognitive tasks. The session began with a 5–10 minute warm-up consisting of slow, gentle Tai Chi movements performed in water to stretch muscles and improve balance. The main training phase included water-based jumping jacks (20 × 2 sets), water-based punch and kick (20 × 2 sets), alternate high-knee running (20 reps × 3 sets), water-running (25 m × 4 sets), and flutter kicking at the pool edge (3 min × 4 sets). These exercises were performed with progressive intensity to match the target heart rate zones. During the main exercises, participants simultaneously performed cognitive tasks (e.g., mental arithmetic, word recall, or answering questions) while moving in water, creating an integrated cognitive-motor

dual-task component. The quality of movement and cognitive performance was closely monitored by the instructor. The session concluded with a 5–10 minute cool-down consisting of water-based stretching to gradually lower heart rate and relax muscles.

**Aquatic High-Intensity Interval Training Group**

The AHIIT program consisted of 60-minute sessions of progressive aquatic exercises without additional cognitive loading. Each session started with a 5–10 minute warm-up of slow, gentle Tai Chi movements in water. The main training component included water-based jumping jacks (20 × 2 sets), water-based punch and kick (20 × 2 sets), alternate high-knee movements (20 reps × 3 sets), water-running simulating running motion (25 m × 4 sets), and flutter kicking at the pool edge (3 min × 4 sets). All exercises were performed at the prescribed heart rate intensity, emphasizing powerful movements against water resistance while maintaining proper body alignment and posture. The session ended with a 5–10 minute cool-down of water-based stretching exercises (Figure 3).

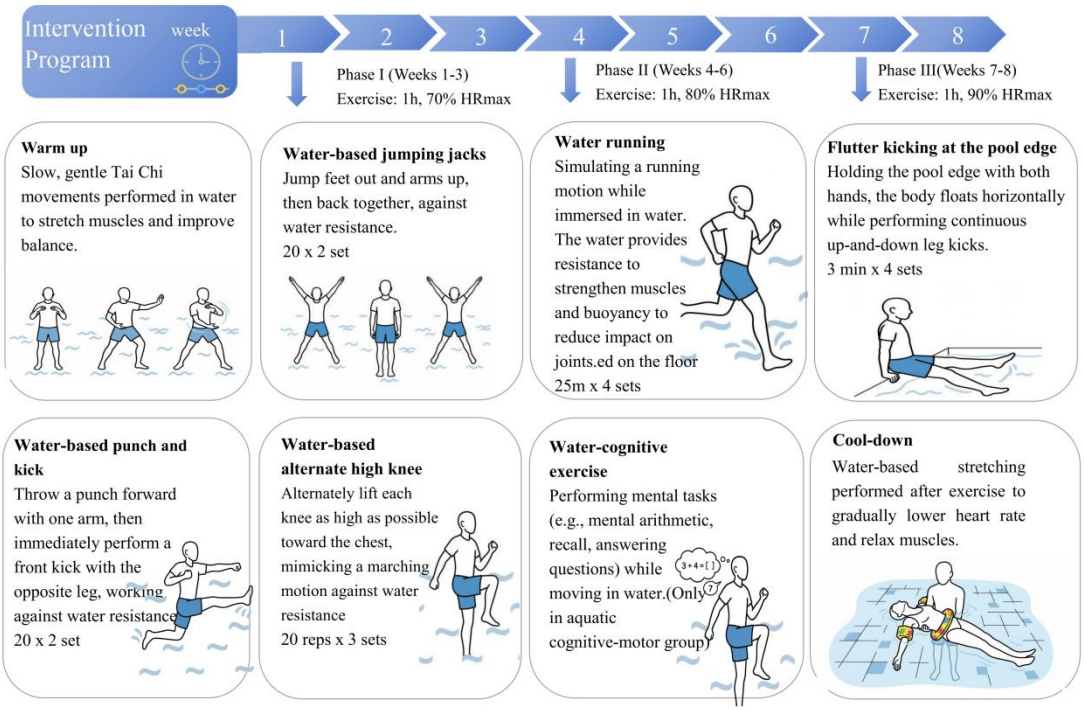


**Figure 3. Structure and progression of the 8-week aquatic exercise intervention**

## Outcomes

### Balance Performance

Balance performance was assessed through both functional clinical tests and instrumented postural sway measurements. Functional clinical tests included the YBT (with composite scores normalized to leg length and summed to obtain the composite score)[27]. Instrumented postural sway was recorded with a BTrackS portable force plate (Balance Tracking Systems, San Diego, CA, USA), which captured displacement of the center of pressure (COP) during quiet standing at a sampling rate of 25 Hz using the BTrackS Explore Balance software (v2.0.4). Three stance conditions were performed barefoot in a fixed order: (1) parallel (double-leg) stance, with feet shoulder-width apart; (2) single-leg stance on the left limb; and (3) single-leg stance on the right limb. For each condition, three 20-s trials were performed, with participants instructed

to stand as still as possible with arms relaxed at the sides and gaze fixed on a marker placed at eye level approximately 2 m away. A 30-s seated rest separated trials, and a 1-min rest separated conditions, to minimize fatigue. A research assistant stood adjacent to the plate at all times to prevent falls. The following COP-derived parameters were computed offline for each condition: sway path total (mm), sway velocity total ($mm \cdot s^{-1}$), maximum anteroposterior (A-P) and mediolateral (M-L) sway amplitude (mm), sway area total ($mm^2$), sway area per second ($mm^2 \cdot s^{-1}$), and the area of the 100% confidence ellipse ($mm^2$)[29].

**fNIRS Data Acquisition and Preprocessing**

Task-dependent cortical activity was acquired simultaneously with the force-plate recordings using a portable continuous-wave fNIRS system, NIRSport2 (NIRx Medical Technologies, LLC, Berlin, Germany), with two emission wavelengths (760 nm and 850 nm) and a sampling rate of 10.2 Hz[30,31]. Data were acquired with Aurora fNIRS software (v2021.9, NIRx Medical Technologies, LLC, Berlin, Germany). Cortical hemodynamic activity was indexed by changes in oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) concentration. HbO was selected as the primary outcome owing to its higher signal-to-noise ratio, superior test–retest reliability, and greater sensitivity to task-evoked cortical blood flow changes compared with HbR[32].

The probe montage consisted of 16 light sources and 16 detectors anchored to the 10–10 international system, yielding a total of 52 long-separation measurement channels distributed bilaterally over the frontopolar, prefrontal, frontocentral, central,

and centroparietal scalp regions[33]. Source–detector separation was kept at approximately 3.0–4.5 cm to ensure adequate light penetration through the scalp and skull into cortical grey matter[34]. Channels were grouped a priori into five anatomically defined regions of interest (ROIs) based on their position in the 10–10 system: the frontopolar region (Fp-row channels), the prefrontal region (AF- and F-row channels), the frontocentral region (FC-row channels), the central region (C-row channels), and the centroparietal region (CP- and P-row channels) (Supplementary Table 1,Supplementary Figure 1).

Raw fNIRS data were preprocessed using NirSpark software (Danyang HuiChuang Medical Equipment Co., Ltd., Danyang, Jiangsu, China). The pipeline comprised the following steps: (1) conversion of raw light-intensity signals to optical density; (2) correction of motion artefacts using spline interpolation[35,36]; (3) band-pass filtering from 0.01 Hz to 0.2 Hz to attenuate physiological noise[31]; (4) conversion of denoised optical-density data to haemoglobin concentration values; and (5) calculation of relative changes in oxyhaemoglobin (HbO) concentration via the modified Beer–Lambert law[37]. Channel-level data quality was screened using a scalp coupling index (SCI) threshold, below which channels were excluded prior to analysis[38]. Block-averaged HbO time courses were computed for each stance condition, and the mean HbO value during the 20-s stance window was extracted for each ROI as the primary index of task-dependent cortical activation.

For the brain-region-level analysis, the five original regions of interest (ROIs) were further consolidated into two broader functional regions according to their

anatomical proximity and predominant functional roles[39–41]. The frontopolar and prefrontal ROIs were combined to form the prefrontal cognitive-control region, reflecting their shared involvement in executive control, attentional allocation, and task monitoring. The frontocentral, central, and centroparietal ROIs were combined to form the motor and sensorimotor control region, given their collective involvement in motor planning, movement execution, somatosensory processing, and sensorimotor integration[39,42].

For each participant, stance condition, and assessment time point, the value of the prefrontal cognitive-control region was calculated as the arithmetic mean of the frontopolar and prefrontal ROI HbO values. The value of the motor and sensorimotor control region was calculated as the arithmetic mean of the frontocentral, central, and centroparietal ROI HbO values. Regional consolidation was performed at the participant level before group-level statistical analysis. Because this broader functional classification was introduced to facilitate interpretation and reduce the number of regional comparisons, the two-region analysis was considered exploratory.

**Statistical Analysis**

All statistical analyses were performed in Python (version 3.12; Python Software Foundation), using the Pingouin and Statsmodels packages. Statistical significance was set at $P < 0.05$. Data are presented as mean ± standard deviation (SD). Normality of data distribution was assessed using the Shapiro–Wilk test, and homogeneity of variances was examined with Levene's test. Given the modest sample size and the skewed distributions of several force-plate parameters, the mixed-design

ANOVA was retained for its robustness to moderate violations of normality, and results were interpreted alongside effect sizes.

For cognitive scores (MoCA), functional performance measures (YBT [left and right], 30-s CST, and TUG), and postural balance outcomes (force-plate parameters in each stance condition), a two-way mixed-design analysis of variance (mixed ANOVA) was conducted with Group (ACME vs. AHIIT) as the between-subjects factor and Time (pre- vs. post-intervention) as the within-subjects factor. This model yielded three effects of interest: the main effect of Group, the main effect of Time, and the Group × Time interaction. Partial eta squared ($\eta p^2$) was calculated as a measure of effect size for all ANOVA results.

For the fNIRS data, mean HbO concentration during each stance condition (parallel, single-leg left, single-leg right) in the five cortical regions of interest was analyzed using a two-way mixed-design ANOVA with Group (ACME vs. AHIIT) as the between-subjects factor and Time (pre- vs. post-intervention) as the within-subjects factor. This approach yielded Group, Time, and Group × Time interaction effects for HbO in each region and stance condition. For exploratory functional-region analysis, the five original ROIs were consolidated at the participant level into two broader regions: the prefrontal cognitive-control region (mean of the frontopolar and prefrontal ROIs) and the motor and sensorimotor control region (mean of the frontocentral, central, and centroparietal ROIs)[39–42]. Each region was analyzed using a two-way mixed-design ANOVA with Group as the between-subjects factor and Time as the within-subjects factor. Partial eta squared ($\eta p^2$) was reported, and Group × Time interactions

were further characterized using between-group differences in change scores, 95% confidence intervals, and Hedges' g. Holm-adjusted p values were reported for the six interaction tests, with findings significant only before adjustment interpreted as exploratory. To further characterize within-group patterns of regional cortical activation at each time point, Friedman non-parametric tests were conducted across the five ROIs within each group and time point, given the small sample size. Where the Friedman test yielded a significant result, pairwise post-hoc comparisons between ROIs were performed using Wilcoxon signed-rank tests with Bonferroni correction.

## RESULTS

The mean ages of participants in the ACME group and AHIIT groups were 67.50 ± 4.93 and 67.83 ± 3.95 yr, respectively. Participant anthropometric characteristics, in terms of height, body weight, and body mass index (BMI) are shown(Table 1).

**Table 1. Anthropometric parameters.**

| Parameters | ACME (n = 10) | AHIIT (n = 12) |
|---|---|---|
| Age (yr) | 67.50 ± 4.93 | 67.83 ± 3.95 |
| Height (m) | 1.63 ± 0.08 | 1.64 ± 0.07 |
| Weight (kg) | 71.04 ± 5.98 | 65.90 ± 6.95 |
| BMI ($kg \cdot m^{-2}$) | 26.93 ± 2.72 | 24.61 ± 2.92 |

### Cognitive Function and Functional Performance

Cognitive and functional outcomes are presented(Table 2). For the MoCA, a significant main effect of Time was observed ($F(1, 20) = 97.471$, $p < 0.001$, $\eta p^2 = 0.83$), whereas neither the main effect of Group ($F(1, 20) = 0.251$, $p = 0.6217$, $\eta p^2 = 0.01$) nor the Group × Time interaction was significant ($F(1, 20) = 0.006$, $p = 0.9409$, $\eta p^2 = 0.00$).

Scores improved after training in both groups (ACME: 21.70 ± 2.00 to 25.00 ± 1.94; AHIIT: 22.08 ± 1.62 to 25.33 ± 1.83).

For the Left-leg YBT, significant main effects of Time ($F(1, 20) = 57.668$, $p < 0.001$, $\eta p^2 = 0.74$) and Group ($F(1, 20) = 5.418$, $p = 0.0305$, $\eta p^2 = 0.21$), as well as a significant Group × Time interaction ($F(1, 20) = 14.931$, $p < 0.001$, $\eta p^2 = 0.43$), were observed. The significant interaction indicated that the post-training improvement was substantially greater in the ACME group (87.75 ± 5.92 to 97.59 ± 8.90) than in the AHIIT group (84.75 ± 5.47 to 88.13 ± 5.70). For the Right-leg YBT, significant main effects of Time ($F(1, 20) = 16.226$, $p < 0.001$, $\eta p^2 = 0.45$) and Group ($F(1, 20) = 5.640$, $p = 0.0277$, $\eta p^2 = 0.22$) were observed. However, the Group × Time interaction did not reach statistical significance ($F(1, 20) = 3.687$, $p = 0.0692$, $\eta p^2 = 0.16$). Composite score improved after training in both groups (ACME: 89.17 ± 5.50 to 100.51 ± 13.26; AHIIT: 86.26 ± 4.43 to 90.47 ± 5.26), with the ACME group demonstrating higher values overall.

For the 30-s sit-to-stand test, the main effect of Group was not significant ($F(1, 20) = 3.116$, $p = 0.0928$, $\eta p^2 = 0.13$). Neither the Time effect ($F(1, 20) = 1.121$, $p = 0.3022$, $\eta p^2 = 0.05$) nor the interaction ($F(1, 20) = 0.096$, $p = 0.7603$, $\eta p^2 = 0.00$) was significant. The number of repetitions changed from 19.50 ± 3.44 to 20.10 ± 4.72 in the ACME group and from 17.42 ± 1.88 to 17.75 ± 1.86 in the AHIIT group. For the TUG, a significant main effect of Time was observed ($F(1, 20) = 12.331$, $p = 0.0022$, $\eta p^2 = 0.38$). Neither the main effect of Group ($F(1, 20) = 1.661$, $p = 0.2122$, $\eta p^2 = 0.08$) nor the Group × Time interaction ($F(1, 20) = 0.146$, $p = 0.7064$, $\eta p^2 = 0.01$) was significant.

Completion time decreased after training in both the ACME group (9.07 ± 1.03 to 8.40 ± 1.22) and the AHIIT group (8.21 ± 1.94 to 7.67 ± 1.48).

**Table 2. Cognitive Function and Functional Performance Outcomes in ACME and AHIIT Groups Before and After Intervention (mean ± SD).**

| Parameter | ACME (n = 10) | | AHIIT (n = 12) | | Group Effect | | Time Effect | | Group-Time Effect | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Pretraining | Posttraining | Pretraining | Posttraining | P Value | ηp² | P Value | ηp² | P Value | ηp² |
| MoCA(points) | 21.70±2.00 | 25.00±1.94 | 22.08±1.62 | 25.33±1.83 | 0.6217 | 0.01 | <0.001* | 0.83 | 0.9409 | 0.00 |
| Y-Balance Left(%) | 87.75±5.92 | 97.59±8.90 | 84.75±5.47 | 88.13±5.70 | 0.0305* | 0.21 | <0.001* | 0.74 | <0.001* | 0.43 |
| Y-Balance Right(%) | 89.17±5.50 | 100.51±13.26 | 86.26±4.43 | 90.47±5.26 | 0.0277* | 0.22 | <0.001* | 0.45 | 0.0692 | 0.16 |
| 30-s Sit-to-Stand(repetitions) | 19.50±3.44 | 20.10±4.72 | 17.42±1.88 | 17.75±1.86 | 0.0928 | 0.13 | 0.3022 | 0.05 | 0.7603 | 0.00 |
| Timed Up and Go (s) | 9.07±1.03 | 8.40±1.22 | 8.21±1.94 | 7.67±1.48 | 0.2122 | 0.08 | 0.0022* | 0.38 | 0.7064 | 0.01 |

**Force Plate Balance**

**Parallel Stance**

Significant main effects of Time were observed for most postural sway variables, indicating reduced sway following training in both groups, including sway path length ($F(1, 20) = 22.6$, $p < 0.001$, $\eta p^2 = 0.53$), total sway velocity ($F(1, 20) = 19.2$, $p < 0.001$, $\eta p^2 = 0.49$), total sway area ($F(1, 20) = 16.0$, $p = 0.0007$, $\eta p^2 = 0.44$), sway area per second ($F(1, 20) = 14.2$, $p = 0.0012$, $\eta p^2 = 0.41$) and maximum mediolateral amplitude ($F(1, 20) = 8.5$, $p = 0.009$, $\eta p^2 = 0.30$). Significant Group × Time interactions were observed for maximum anteroposterior amplitude ($F(1, 20) = 4.4$, $p = 0.0480$, $\eta p^2 =$

0.18) and maximum mediolateral amplitude ($F(1, 20) = 4.1$, $p = 0.0486$, $\eta p^2 = 0.18$). These interactions indicated greater reductions in sway amplitude in the ACME group (A-P: 29.59 ± 11.40 to 21.85 ± 8.33; M-L: 41.87 ± 13.15 to 14.24 ± 9.83) than in the AHIIT group. The main effect of was not significant for anteroposterior maximum amplitude ($p = 0.235$), and neither the time effect nor the interaction was significant for the area of the 100% ellipse (both $p \geq 0.11$) (Table 3).

**Single-Leg Stance (Left)**

Significant main effects of Time were observed for sway path length ($F(1, 20) = 18.5$, $p < 0.001$, $\eta p^2 = 0.48$), total sway velocity ($F(1, 20) = 30.5$, $p < 0.001$, $\eta p^2 = 0.60$), maximum anteroposterior amplitude ($F(1, 20) = 8.9$, $p = 0.008$, $\eta p^2 = 0.31$) and maximum mediolateral amplitude ($F(1, 20) = 8.4$, $p = 0.009$, $\eta p^2 = 0.30$), indicating reduced sway after training. Significant Group × Time interactions were observed for total sway velocity ($F(1, 20) = 29.7$, $p < 0.001$, $\eta p^2 = 0.60$), maximum anteroposterior amplitude ($F(1, 20) = 5.8$, $p = 0.025$, $\eta p^2 = 0.23$) and maximum mediolateral amplitude ($F(1, 20) = 9.2$, $p = 0.007$, $\eta p^2 = 0.31$). In each case, the reductions in sway were greater in the ACME group (e.g., sway velocity 88.45 ± 30.86 to 50.85 ± 19.27) than in the AHIIT group (58.47 ± 14.75 to 56.70 ± 9.62). The areal parameters (total sway area, sway area per second, area of the 100% ellipse) showed no significant effects (all $p \geq 0.05$), and no group effect was significant for any parameter (all $p \geq 0.13$) (Table 3).

**Single-Leg Stance (Right)**

Significant main effects for total sway path ($F(1, 20) = 16.3$, $p < 0.001$, $\eta p^2 = 0.45$), total sway velocity ($F(1, 20) = 17.4$, $p < 0.001$, $\eta p^2 = 0.46$), maximum

anteroposterior amplitude ($F(1, 20) = 17.0$, $p < 0.001$, $\eta p^2 = 0.46$), total sway area ($F(1, 20) = 12.9$, $p = 0.002$, $\eta p^2 = 0.39$), sway area per second ($F(1, 20) = 12.7$, $p = 0.002$, $\eta p^2 = 0.39$) and area of the 100% ellipse ($F(1, 20) = 7.2$, $p = 0.014$, $\eta p^2 = 0.27$), indicating reduced sway after training in both groups. In contrast to the left stance, several group effects emerged: maximum anteroposterior amplitude ($F(1, 20) = 6.7$, $p = 0.018$, $\eta p^2 = 0.25$), maximum mediolateral amplitude ($F(1, 20) = 8.0$, $p = 0.011$, $\eta p^2 = 0.28$), total sway area ($F(1, 20) = 4.7$, $p = 0.043$, $\eta p^2 = 0.19$), sway area per second ($F(1, 20) = 4.8$, $p = 0.040$, $\eta p^2 = 0.19$) and area of the 100% ellipse ($F(1, 20) = 8.5$, $p = 0.009$, $\eta p^2 = 0.30$). with the AHIIT group exhibiting greater sway overall than the ACME group (e.g., A-P maximum amplitude 82.29 ± 37.47 vs 57.91 ± 21.63 before training). No Group × Time interaction was significant for any parameter (all $p > 0.09$) (Table 3).

**Table 3. Postural Balance Outcomes in Exp and Ctrl Groups Before and After Intervention (mean ± SD)**

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Insert Table 3 about here

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**fNIRS Task-Dependent Neural Activity**

**Parallel Stance**

In the frontopolar region, significant main effects of Group ($F(1, 20) = 10.4$, $p = 0.004$, $\eta p^2 = 0.34$) and Group × Time interaction ($F(1, 20) = 6.2$, $p = 0.021$, $\eta p^2 = 0.24$) were observed, whereas the main effect of Time was not significant ($F(1, 20) =$

0.8, p = 0.392, $\eta p^2$ = 0.04). The interaction indicated opposite changes across groups: frontopolar HbO increased from pre- to post-training in the ACME group (−3.80 ± 2.67 to 0.11 ± 1.69) but decreased in the AHIIT group (1.43 ± 4.96 to −0.09 ± 1.61), and the ACME group showed lower frontopolar HbO overall. A time effect was also found in the centroparietal region (F(1, 20) = 4.7, p = 0.042, $\eta p^2$ = 0.19), indicating greater HbO after training in both groups ( ACME: −0.45 ± 0.37 to 1.94 ± 4.60; AHIIT: 0.00 ± 0.54 to 0.67 ± 0.85), with no Group effect (p = 0.561) or Group × Time interaction (p = 0.210). No significant effects were observed in the prefrontal, frontocentral, or central regions (all p > 0.16). Within-group analyses across the five ROIs (Friedman tests) revealed significant regional heterogeneity in the ACME group before training ($\chi^2(4)$ = 16.16, p = 0.003) but not after training ($\chi^2(4)$ = 0.16, p = 0.997). In the AHIIT group, regional HbO did not differ significantly across ROIs at either time point (before: $\chi^2(4)$ = 1.87, p = 0.760; after: $\chi^2(4)$ = 3.33, p = 0.504). The significant pre-training heterogeneity in the ACME group exhibited markedly lower (more negative) frontopolar HbO relative to the other four regions, although no individual pairwise comparison survived Bonferroni correction (Wilcoxon signed-rank, all p ≥ 0.006) (Table 4).

**Single-Leg Stance (Left)**

No significant main effects of Group or Time, nor any significant Group × Time interactions, were observed in any of the five cortical regions (all p > 0.08). The largest, albeit non-significant, effect was observed for the Group × Time interaction in the frontopolar region (F(1, 20) = 3.3, p = 0.086, $\eta p^2$ = 0.14). This pattern reflected a

417 decrease in HbO from pre- to post-training in the ACME group (7.61 ± 13.50 to −0.26
418 ± 3.91) that was not evident in the AHIIT group (1.22 ± 4.64 to 1.32 ± 3.67). Across the
419 five ROIs, regional HbO did not differ significantly in either group at either time point
420 (Friedman tests, all $p > 0.13$) (Table 4).

421 **Single-Leg Stance (Right)**

422 In the frontopolar region, significant main effects of Time ($F(1, 20) = 6.6$, $p =$
423 $0.018$, $\eta p^2 = 0.25$) and Group × Time interaction ($F(1, 20) = 5.5$, $p = 0.030$, $\eta p^2 = 0.22$)
424 were observed, whereas the main effect of Group was not significant ($F(1, 20) = 1.5$, $p$
425 $= 0.243$, $\eta p^2 = 0.07$). Frontopolar HbO decreased from pre- to post-training overall, and
426 the interaction indicated that this decrease was substantially greater in the ACME group
427 (9.01 ± 11.19 to −1.81 ± 11.69) than in the AHIIT group (0.77 ± 3.38 to −0.14 ± 3.28).
428 No significant effects were observed in the remaining regions (all $p > 0.12$), although
429 non-significant group-level trends were noted in the frontocentral ($F(1, 20) = 2.6$, $p =$
430 $0.125$, $\eta p^2 = 0.11$) and central ($F(1, 20) = 2.2$, $p = 0.156$, $\eta p^2 = 0.10$) regions. Within-
431 group analyses across the five ROIs showed significant regional heterogeneity in the
432 ACME group before training ($\chi^2(4) = 20.48$, $p < 0.001$) but not after training ($\chi^2(4) =$
433 $2.00$, $p = 0.736$); in the AHIIT group, regional HbO did not differ across ROIs at either
434 time point (before: $\chi^2(4) = 2.60$, $p = 0.627$; after: $\chi^2(4) = 3.67$, $p = 0.453$). Post-hoc
435 Wilcoxon signed-rank tests indicated that, before training, frontopolar HbO was
436 significantly higher than in each of the other four regions (all $p \leq 0.004$, surviving
437 Bonferroni correction) (Figure 4, Table 4).

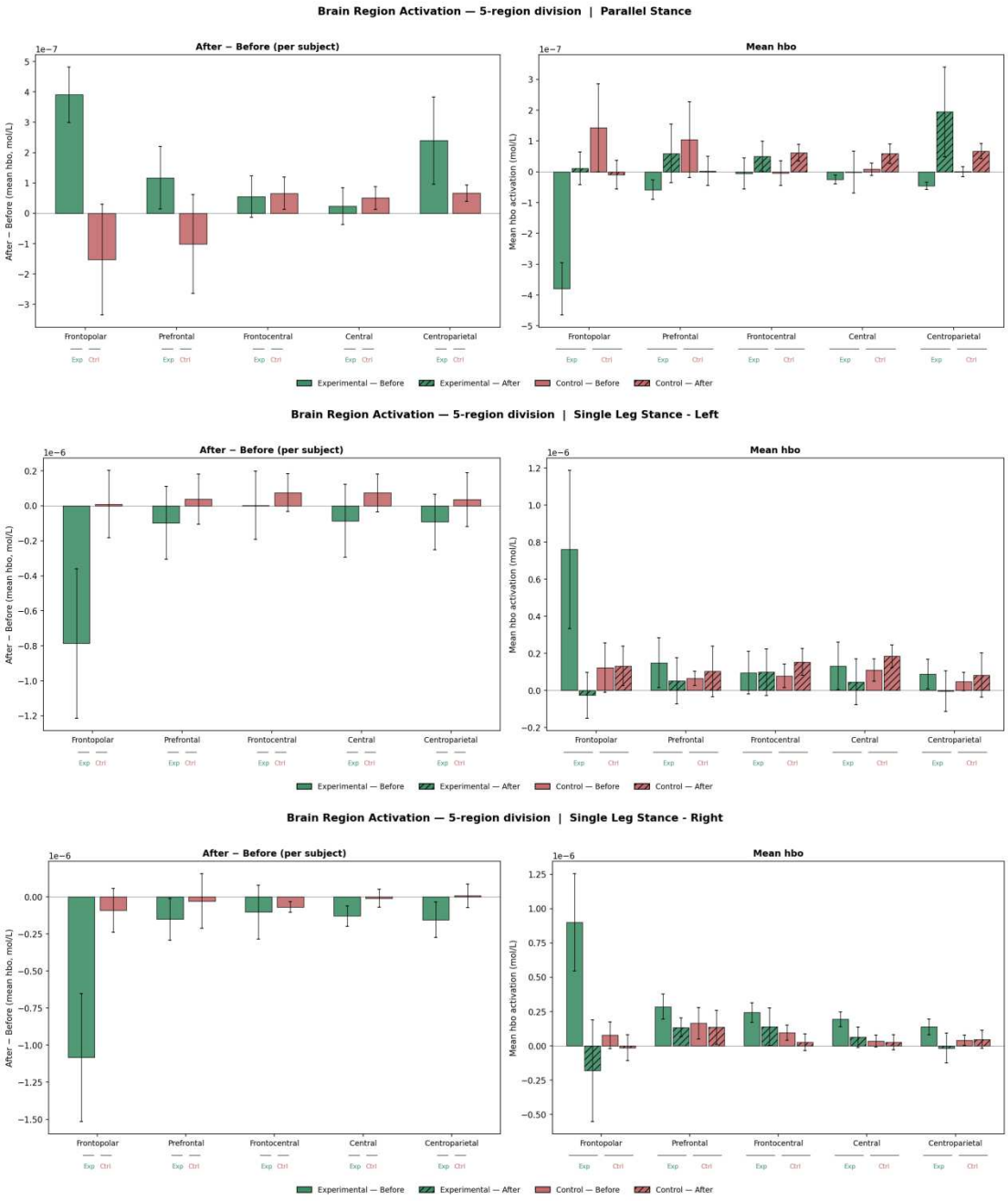


**Figure 5. Changes in task-dependent HbO activation across five cortical regions under different stance conditions**

**Table 4. Task-Dependent HbO Cortical Activation in ACME and AHIIT Groups by Brain Region and Stance Condition (mean ± SD)**

| Brain Region | ACME (n = 10) | | AHIIT (n = 12) | | Group Effect | | Time Effect | | Group-Time Effect | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Pretraining | Posttraining | Pretraining | Posttraining | P Value | $\eta p^2$ | P Value | $\eta p^2$ | P Value | $\eta p^2$ |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Parallel Stance** | | | | | | | | | | |
| Frontopolar | -3.80 ± 2.67 | 0.11 ± 1.69 | 1.43 ± 4.96 | -0.09 ± 1.61 | 0.0042 * | 0.34 | 0.3922 | 0.04 | 0.0214 * | 0.24 |
| Prefrontal | -0.58 ± 1.02 | 0.59 ± 3.01 | 1.04 ± 4.28 | 0.03 ± 1.63 | 0.4409 | 0.03 | 0.9839 | 0.00 | 0.2915 | 0.06 |
| Frontocentral | -0.06 ± 1.59 | 0.50 ± 1.57 | -0.04 ± 1.39 | 0.62 ± 0.93 | 0.8728 | 0.00 | 0.1656 | 0.09 | 0.9032 | 0.00 |
| Central | -0.25 ± 0.47 | -0.01 ± 2.15 | 0.08 ± 0.71 | 0.59 ± 1.08 | 0.2651 | 0.06 | 0.2809 | 0.06 | 0.7005 | 0.01 |
| Centroparietal | -0.45 ± 0.37 | 1.94 ± 4.60 | 0.00 ± 0.54 | 0.67 ± 0.85 | 0.5608 | 0.02 | 0.0416 * | 0.19 | 0.2100 | 0.08 |
| **Single-Leg Stance (Left)** | | | | | | | | | | |
| Frontopolar | 7.61 ± 13.50 | -0.26 ± 3.91 | 1.22 ± 4.64 | 1.32 ± 3.67 | 0.2975 | 0.05 | 0.1246 | 0.11 | 0.0864 | 0.14 |
| Prefrontal | 1.49 ± 4.23 | 0.51 ± 3.95 | 0.64 ± 1.35 | 1.03 ± 4.74 | 0.8722 | 0.00 | 0.8512 | 0.00 | 0.5869 | 0.02 |
| Frontocentral | 0.96 ± 3.65 | 0.99 ± 3.98 | 0.78 ± 2.19 | 1.53 ± 2.48 | 0.8178 | 0.00 | 0.6921 | 0.01 | 0.7367 | 0.01 |
| Central | 1.32 ± 4.07 | 0.46 ± 3.92 | 1.10 ± 2.07 | 1.84 ± 2.16 | 0.4321 | 0.03 | 0.9936 | 0.00 | 0.4815 | 0.03 |
| Centroparietal | 0.88 ± 2.50 | -0.05 ± 3.47 | 0.47 ± 1.73 | 0.82 ± 4.12 | 0.7500 | 0.01 | 0.8387 | 0.00 | 0.5746 | 0.02 |
| **Single-Leg Stance (Right)** | | | | | | | | | | |
| Frontopolar | 9.01 ± 11.19 | -1.81 ± 11.69 | 0.77 ± 3.38 | -0.14 ± 3.28 | 0.2429 | 0.07 | 0.0183 * | 0.25 | 0.0297 * | 0.22 |
| Prefrontal | 2.85 ± 2.91 | 1.34 ± 2.15 | 1.64 ± 3.94 | 1.35 ± 4.27 | 0.5130 | 0.02 | 0.4871 | 0.02 | 0.6133 | 0.01 |
| Frontocentral | 2.43 ± 2.25 | 1.40 ± 4.32 | 0.94 ± 1.90 | 0.25 ± 2.11 | 0.1246 | 0.11 | 0.3271 | 0.05 | 0.8420 | 0.00 |
| Central | 1.93 ± 1.72 | 0.63 ± 2.33 | 0.36 ± 1.51 | 0.26 ± 1.90 | 0.1555 | 0.10 | 0.1736 | 0.09 | 0.2036 | 0.08 |
| Centroparietal | 1.38 ± 1.79 | -0.17 ± 3.43 | 0.40 ± 1.29 | 0.47 ± 2.26 | 0.8123 | 0.00 | 0.3472 | 0.04 | 0.2591 | 0.06 |

*Values are presented as mean ± SD in HbO ($\times 10^{-7}$ mol/L).*

**Exploratory Functional-Region Analysis**

The exploratory analysis of the two broader functional regions revealed a Group

× Time interaction for the prefrontal cognitive-control region during right single-leg stance before multiplicity adjustment ($F(1, 20) = 5.42$, $p = 0.030$, $\eta p^2 = 0.21$). HbO concentration decreased from $5.93 \pm 6.51$ to $-0.24 \pm 5.22 \times 10^{-7}$ mol/L in the ACME group and from $1.21 \pm 3.19$ to $0.61 \pm 2.66 \times 10^{-7}$ mol/L in the AHIIT group. The between-group difference in change scores was $-5.57 \times 10^{-7}$ mol/L (95% CI: −10.56 to −0.58; Hedges' $g = -0.96$), indicating a greater reduction in the ACME group. However, this interaction did not remain significant after Holm correction (adjusted $p = 0.183$) and was therefore interpreted as exploratory.

No significant Group × Time interactions were observed for the remaining stance condition–region combinations (all unadjusted $p \geq 0.074$). The interaction for the prefrontal cognitive-control region during parallel stance showed a moderate-to-large effect but did not reach statistical significance ($F(1, 20) = 3.56$, $p = 0.074$, $\eta p^2 = 0.15$; Hedges' $g = 0.78$). Before multiplicity adjustment, a Group effect was observed for the prefrontal cognitive-control region during parallel stance ($p = 0.038$), while Time effects were observed for the motor and sensorimotor control region during parallel stance ($p = 0.021$) and the prefrontal cognitive-control region during right single-leg stance ($p = 0.016$). None of these effects remained significant after Holm correction (all adjusted $p \geq 0.097$)(Supplementary Table 2).

## DISCUSSION

The primary aim of this study was to compare the effects of an 8-week ACME program with an AHIIT program of equivalent intensity on postural control, prefrontal

cortical activity, and cognitive function in older adults with MCI. To our knowledge, this is one of the first randomized controlled trials to combine fNIRS with three-dimensional force plate assessments to evaluate cognitive and balance function in this population, thereby contributing neuroimaging and instrumented balance data to the aquatic exercise literature. The principal findings were as follows. First, postural sway parameters improved significantly over time in both groups under parallel and single-leg stance conditions, indicating a general time effect of aquatic exercise on postural stability. Second, the ACME group demonstrated substantially greater improvements in dynamic sway control during left single-leg stance compared with the AHIIT group, with significant Group × Time interactions for total sway velocity and maximum A-P and M-L sway amplitudes. Third, fNIRS data revealed a significant Group × Time interaction in frontopolar cortical activation during parallel stance: the ACME group showed a substantially greater increase in HbO concentration, and its cortical regional activation pattern shifted from a heterogeneous to a more balanced distribution. Fourth, the ACME group demonstrated greater improvements in functional mobility (TUG performance) and in dynamic balance as assessed (left-leg YBT performance). Collectively, these fundings indicate that, at equivalent exercise intensities, ACME elicits superior balance and cortical adaptations compared with AHIIT in older adults with MCI. These findings are consistent with prior evidence that dual-task training produces greater improvements than single-task training[43,44]. Imposing cognitive load during physical activity may more effectively promote neural activity in regions such as the prefrontal cortex, which plays a critical role in both postural regulation and

cognitive function. The aquatic environment also provides a safe and efficient training context that facilitates balance improvement[16,45].

## fNIRS Task-Dependent Neural Activity

### Key Findings

The most novel neurophysiological finding of this study is the significant Group x Time interaction observed in frontopolar cortical activation during parallel stance: the ACME group exhibited a mean HbO increase of $+3.91 \times 10^{-7}$ mol/L, whereas the AHIIT group showed a mean decrease of $-1.52 \times 10^{-7}$ mol/L. This divergence in frontopolar hemodynamic responses following 8 weeks of intervention indicates that aquatic exercise combined with concurrent cognitive tasks induced unique neuroplastic adaptations in this region — adaptations not produced by high-intensity physical training alone.

### Interpretation of Prefrontal Mechanisms

The prefrontal cortex plays a key role in prospective memory, multitasking, branching cognition, attentional control and executive function[46–49] — precisely the cognitive processes repeatedly engaged when ACME participants performed mental arithmetic and word recall tasks while exercising in water. Systematic reviews and network meta-analyses have shown that dual-task training combining cognitive tasks with physical activity more effectively improves executive function and prefrontal-related cognition in older adults — particularly those with cognitive impairment — compared with either physical or cognitive training alone[43,44]. Accordingly, 8 weeks of sustained dual-task training may have specifically strengthened frontopolar cortical

recruitment of executive resources, and this enhancement transferred to the subsequent postural control task, consistent with the prefrontal cortex–posture hypothesis[9,50]. By contrast, the absence of a frontopolar HbO increase in the AHIIT group suggests that physical training alone did not produce the corresponding executive cortical adaptation.

**Parallel Stance**

Within-group analyses further support this interpretation. In the ACME group during parallel stance, regional cortical activation was significantly heterogeneous before the intervention, driven by markedly lower (more negative) frontopolar HbO relative to the other regions, but shifted to a more balanced distribution after the intervention, with a descriptive trend toward increased centroparietal involvement. In contrast, the AHIIT group's regional activation patterns remained relatively stable across time points. The transition from frontopolar-dominant, uneven activation to a more balanced and distributed pattern incorporating greater centroparietal (sensorimotor integration-related) involvement may reflect the establishment of a more integrated frontoparietal cortical network in the ACME group. Given that aging is commonly associated with a shift from automatic to cortically dependent postural control, and that balance training can induce plastic reorganization of relevant cortical circuits[50], this redistribution of activation may represent a more optimized cortical control strategy — one that aligns directionally with the improvements in force plate postural stability observed in the same group. Previous interventional fNIRS studies have demonstrated that structured training can alter task-dependent cortical activity

during balance tasks: Fujimoto et al. (2014) reported enhanced supplementary motor area activation following rehabilitation in stroke patients[51], and Hernandez-Sarabia et al. (2024) showed that yoga or exercise interventions altered cortical activity during balance tasks in adults with acquired brain injury, with region-specific increases and decreases in activation[52]. These findings collectively support the view that exercise interventions can modify balance-related cortical activity.

**Single-Leg Stance**

Under the more challenging single-leg stance conditions, the pattern differed between the two legs. During left single-leg stance, no cortical region showed a significant Group × Time interaction (all $p > 0.08$), whereas during right single-leg stance a significant interaction emerged in the frontopolar region ($F(1, 20) = 5.5$, $p = 0.030$, $\eta p^2 = 0.22$). In both legs, the largest between-group difference was in the frontopolar region, where the ACME group showed a marked HbO decrease while the AHIIT group remained relatively stable (left: ACME $-7.87 \pm 13.48$ vs AHIIT $+0.10 \pm 6.68 \times 10^{-7}$ mol/L, $p = 0.086$; right: ACME $-10.83 \pm 13.62$ vs AHIIT $-0.91 \pm 5.11 \times 10^{-7}$ mol/L, $p = 0.030$). Notably, frontopolar activation showed opposite directional changes across task difficulty levels: it increased during the easier parallel stance but decreased during the more demanding single-leg stance. This task-dependent bidirectional pattern may be interpreted through the neural efficiency hypothesis[53]. The reduced executive frontopolar engagement during high-demand postural tasks in the ACME group — significant on the dominant (right) side and showing a concordant trend on the left — suggests enhanced automaticity of postural control[54]. This is

consistent with evidence that exercise interventions can reduce prefrontal activation during walking in older adults alongside improvements in executive function[51]. In particular, the combination of greater postural improvement and reduced frontopolar activation during single-leg stance in the ACME group is characteristic of neural efficiency — achieving comparable or better performance with less prefrontal effort. Because the left-side difference only approached significance and the overall sample was small, this interpretation should nonetheless be regarded with appropriate caution. Furthermore, in the ACME group, pre-intervention cortical activation under right single-leg stance was significantly dominated by the frontopolar region, but became more evenly distributed across regions post-intervention, while the AHIIT group maintained stable regional patterns throughout. This shift from frontopolar-dominant to distributed activation, together with the significant reduction in frontopolar HbO during right single-leg stance, is consistent with reduced reliance on prefrontal executive control and a transition toward more automated postural regulation [53]. Notably, this neural change occurred despite the absence of a significant Group × Time interaction in the right single-leg stance force plate data, suggesting that, for the dominant limb — whose postural control is inherently more automatic — the ACME group intervention manifested primarily as more efficient cortical processing (lower and more evenly distributed activation) rather than as a further measurable gain in mechanical stability.

**Exploratory Functional-Region**

Comparisons of the magnitude and direction of HbO changes in the motor and sensorimotor control region and prefrontal cognitive-control regions between the two

exercise modalities suggest that ACME and AHIIT may have induced different patterns of task-dependent cortical adaptation. During parallel stance, the ACME group showed a greater increase in the prefrontal cognitive-control region than the AHIIT group (+2.54 vs. −1.27), together with a slightly greater increase in the motor and sensorimotor control region (+1.06 vs. +0.61). Under this relatively stable postural condition, increased HbO may reflect greater recruitment of cortical resources to support attention, executive control, motor planning, and sensory integration[39,40,55]. In contrast, during the more demanding single-leg stance conditions, ACME elicited greater reductions in HbO, particularly in the prefrontal cognitive-control region. During right single-leg stance, the reduction was −6.17 in the ACME group compared with −0.60 in the AHIIT group, corresponding to a large between-group effect size (Hedges' g = −0.96). A similar pattern was observed during left single-leg stance (−4.42 vs. +0.24). Changes in the motor and sensorimotor control region were comparatively smaller, although ACME again produced a greater reduction during right single-leg stance (−1.29 vs. −0.24). Increased cortical activation may indicate enhanced neural recruitment during task acquisition, whereas reduced activation accompanied by maintained or improved behavioral performance may reflect greater neural efficiency, increased automaticity, and reduced reliance on effortful prefrontal control after training[56–59]. Therefore, the greater HbO modulation observed following ACME, particularly within the prefrontal cognitive-control region, may reflect more pronounced task-dependent cortical adaptation. This interpretation is broadly consistent with the greater improvement in dynamic balance observed in the ACME group and

with evidence indicating that combined cognitive-motor training can enhance attentional allocation, postural control, and dual-task performance[60]. In comparison, the smaller and more consistent changes following AHIIT may reflect more generalized cardiovascular or cerebrovascular adaptations rather than task-specific cortical reorganization[23,61]. Nevertheless, these findings should be interpreted cautiously because none of the Group × Time interactions remained significant after correction for multiple comparisons. Furthermore, fNIRS-derived HbO signals may be influenced by systemic and extracerebral hemodynamics[62]. Therefore, the present findings provide exploratory evidence of potentially different patterns of cortical adaptation rather than definitive evidence that either intervention produced superior neural improvements.

## Three-Dimensional Force Plate Differences

### General Effects

The aquatic environment yielded notable improvements in balance performance across both groups. Both groups demonstrated significant main effects of Time on most force plate parameters during parallel stance, including total sway path, total sway velocity, total sway area, and sway area per second (all $p \leq 0.0012$, $\eta p^2 = 0.41–0.53$). These large effect sizes indicate substantial within-group reductions in postural sway irrespective of training type, reflecting the well-established capacity of aquatic exercise to improve postural stability throughenhancements in lower-limb muscular strength, joint proprioception, and vestibular function — findings consistent with previous research[45]. A systematic review and meta-analysis of multiple randomized controlled trials has confirmed that aquatic exercise effectively improves balance in older

adults[45]. The aquatic environment provides continuous multidirectional perturbations that challenge the somatosensory, vestibular, and visual systems simultaneously, thereby promoting adaptive postural responses and sensory reweighting that transfer to quiet standing on land[16].

During parallel stance, significant Group × Time interactions were also observed for maximum M-L amplitude ($p = 0.049$, $\eta p^2 = 0.18$) and maximum A-P amplitude ($p = 0.048$, $\eta p^2 = 0.18$), indicating greater post-training reductions in directional sway amplitude in the ACME group (M-L: 41.87 ± 13.15 to 14.24 ± 9.83; A-P: 29.59 ± 11.40 to 21.85 ± 8.33) than in the AHIIT group, in which these amplitudes changed little (M-L: 36.64 ± 47.25 to 31.38 ± 31.46; A-P: 32.08 ± 13.89 to 33.61 ± 16.28). Given that lateral falls account for a substantial proportion of hip fractures and related injuries in older adults[63], the greater reduction in M-L sway in the ACME group is particularly relevant for fall prevention. Although these effect sizes were moderate ($\eta p^2 = 0.18$) and the sample was small, the concordance of these directional findings with the single-leg stance results strengthens the evidence that adding cognitive load to aquatic exercise enhances directional postural control.

**Left-Leg Findings**

The most clinically and biomechanically informative force plate findings emerged from left single-leg stance. Three parameters showed significant Group × Time interactions: total sway velocity ($p < 0.001$, $\eta p^2 = 0.60$), maximum A-P amplitude ($p = 0.025$, $\eta p^2 = 0.23$), and maximum M-L amplitude ($p = 0.007$, $\eta p^2 = 0.31$). The two areal parameters (total sway area and sway area per second) showed a consistent trend in the

same direction but did not reach significance (interaction $p \approx 0.06$, $\eta p^2 = 0.17$), which may reflect the limited sample size. The ACME group showed large-to-moderate effect sizes for the significant parameters, indicating that the addition of concurrent cognitive demands during aquatic exercise produced substantially greater improvements in unipedal postural control than aquatic exercise alone. This is consistent with the view that combined cognitive-motor dual-task training improves executive function and balance more effectively than single-domain training[44]. However, the literature remains mixed: some randomized controlled trials and meta-analyses have found that combined training does not confer superior balance or motor outcomes over either exercise or cognitive training alone[64]. Silsupadol et al. reported that the benefits of dual-task balance training are often most apparent under dual-task testing conditions, with less pronounced advantages during single-task balance tasks. Interestingly, the present study demonstrated significant ACME-related benefits during quiet single-leg stance, a single-task condition[65]. One possible explanation is that the simultaneous integration of cognitive and motor demands throughout training may have promoted stronger cognitive-postural coupling, resulting in adaptations that transferred even to isolated balance tasks.

The convergence of significant Group × Time interactions across sway velocity and both directional amplitude measures (A-P and M-L), accompanied by a concordant non-significant trend in the areal parameters, indicates a broad enhancement of neuromuscular postural regulation rather than improvement confined to a single direction or measure. Sway velocity is regarded as one of the most sensitive and reliable

COP parameters for detecting subtle changes in postural control, as it integrates both the magnitude and frequency of body oscillations across the full stance trial[66]. The exceptionally large Group × Time interaction effect for sway velocity total during left single-leg stance ($\eta p^2 = 0.60$) indicates that the ACME group achieved faster, more efficient neuromuscular correction of body sway — an improvement likely reflecting dual-task training–specific upregulation of both cortical and subcortical neural circuits governing automatic postural responses. Sway area parameters capture the two-dimensional spatial extent of postural oscillation and provide sensitive indices of cumulative instability over time. Although the Group × Time interactions for the two area measures did not reach significance ($p \approx 0.06$), they were of similar direction and magnitude to the velocity and amplitude effects, suggesting a tendency toward reduced overall COP displacement in the ACME group that may have been constrained by limited statistical power. From a biomechanical perspective, smaller sway areas would indicate more efficient use of the base of support and reduced reactive stabilization demands on the ankle, knee, and hip musculature[67]. Such adaptations would be of particular relevance in individuals with MCI, where impaired executive function and reduced automaticity of postural control are associated with large sway areas, greater temporal sway variability, and elevated fall risk[68], such changes could be clinically meaningful. Nevertheless, given the non-significant interaction effects, this interpretation should be considered preliminary and confirmed in larger studies.

**Right-Leg Findings**

No significant Group × Time interactions were detected in right single-leg

stance (all $p > 0.09$). One possible explanation relates to limb dominance, although evidence regarding lateral asymmetry in postural control remains inconclusive. Some studies have reported minimal differences between limbs during static single-leg stance[69], whereas others have suggested superior balance efficiency and automaticity in the dominant limb[70,71]. Given that most participants in the present study were likely right-leg dominant, right-limb unipedal stance may have been comparatively more automatic and thus afforded less room for further within-study improvement; this interpretation, however, remains tentative pending studies that explicitly stratify by limb dominance. Notably, several right-leg parameters (maximum A-P and M-L amplitudes, sway area total, sway area per second, and 100% ellipse area) showed significant group main effects at both time points (all $p \leq 0.0431$, $\eta p^2 = 0.19–0.30$), with the ACME group generally displaying better performance, suggesting possible baseline advantages that reduced room for further within-study change. Future research should stratify analyses by dominant and non-dominant limb and employ more demanding unipedal conditions (e.g., eyes closed or on compliant surfaces) to reveal potential between-group differences under right-limb loading.

**Limitations**

This study has several limitations. First, the relatively small sample size (ACME: $n = 10$; AHIIT: $n = 12$) may have reduced statistical power. Second, no long-term follow-up assessment was conducted, limiting the ability to determine the durability of the observed balance, cognitive, and neural adaptations. Third, cortical activity was assessed primarily using oxygenated hemoglobin (HbO), without cross-validation using

deoxygenated hemoglobin (HbR) or total hemoglobin measures. In addition, continuous-wave fNIRS can only assess superficial cortical activity and cannot capture the contributions of subcortical structures or the cerebellum, both of which are involved in postural control. Finally, limb dominance was not formally assessed, which may have influenced the asymmetrical findings observed during single-leg stance tasks.

Future studies should include larger, adequately powered samples and longer follow-up periods to confirm the durability and clinical significance of the observed effects. Additional neurophysiological measures, including HbR, short-separation fNIRS channels, and complementary neuroimaging techniques, should be incorporated to better characterize the neural mechanisms underlying aquatic cognitive-motor training.

## CONCLUSION

This randomized controlled trial demonstrated that 8 weeks of aquatic exercise improved cognitive function and postural stability in older adults with mild cognitive impairment. While both interventions produced beneficial effects, aquatic cognitive-motor exercise (ACME) resulted in greater improvements in left single-leg balance performance, dynamic balance, and functional mobility than aquatic high-intensity interval training (AHIIT) of equivalent intensity. Moreover, ACME elicited distinct frontopolar cortical adaptations, characterized by increased task-dependent HbO responses during parallel stance and evidence of more efficient cortical organization during single-leg stance. Exploratory analysis suggested greater task-dependent HbO

modulation after ACME, particularly in the prefrontal cognitive-control region, although this finding did not survive correction for multiple comparisons. These findings suggest that the addition of concurrent cognitive loading may be an important mechanism underlying improvements in balance control and cortical plasticity in older adults with MCI.

## Ethics approval and consent to participate

All study procedures were approved by the Institutional Review Board of Wuhan Sports University (2025164). Written informed consent to participate was obtained from all participants before their inclusion in the study. All procedures performed in this study involving human participants were conducted in accordance with the relevant guidelines and regulations, including the Declaration of Helsinki.

## Consent for publication

All authors and participants have reviewed and approved the final manuscript and agree to its submission and publication.

## Data availability

Data of this study are available upon contacting the corresponding author.

## Competing interests

The authors report no competing interests.


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## Authors' contributions

All authors (J.S., C.Z., T.L., Y.W., K.Y., and X.K.) participated in the trial intervention. J.S., C.Z., and T.L. generated the random allocation sequence.J.S., C.Z., T.L., and Y.W. performed data analysis and drafted the manuscript. K.Y. and X.K. conducted the pre- and post-testing of the trial. All authors reviewed and approved the final version.


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**References**

1. Ward A, Tardiff S, Dye C, Arrighi HM. Rate of conversion from prodromal alzheimer's disease to alzheimer's dementia: a systematic review of the literature. *Dement Geriatr Cogn Disord Extra*. 2013;3(1):321-332. doi:10.1159/000354370

2. Liu X, Chen MH, Yue GH. Postural control dysfunction and balance rehabilitation in older adults with mild cognitive impairment. *Brain Sci*. 2020;10(11):873. doi:10.3390/brainsci10110873

3. Petersen RC, Caracciolo B, Brayne C, Gauthier S, Jelic V, Fratiglioni L. Mild cognitive impairment: a concept in evolution. *J Intern Med*. 2014;275(3):214-228. doi:10.1111/joim.12190

4. Iadecola C. The pathobiology of vascular dementia. *Neuron*. 2013;80(4):844-866. doi:10.1016/j.neuron.2013.10.008

5. Sierra-Marcos A. Regional cerebral blood flow in mild cognitive impairment and alzheimer's disease measured with arterial spin labeling magnetic resonance imaging. *Int J Alzheimer's Dis*. 2017;2017:5479597. doi:10.1155/2017/5479597

6. van Dinther M, Hooghiemstra AM, Bron EE, et al. Lower cerebral blood flow predicts cognitive decline in patients with vascular cognitive impairment. *Alzheimer's Dement: J Alzheimer's Assoc*. 2024;20(1):136-144. doi:10.1002/alz.13408

7. Borges S de M, Radanovic M, Forlenza OV. Fear of falling and falls in older adults with mild cognitive impairment and alzheimer's disease. *Neuropsychol Dev Cogn, B Aging Neuropsychol Cogn*. 2015;22(3):312-321. doi:10.1080/13825585.2014.933770

8. Venegas-Sanabria LC, Cavero-Redondo I, Lorenzo-Garcia P, Sánchez-Vanegas G, Álvarez-Bueno C. Efficacy of nonpharmacological interventions in cognitive impairment: Systematic review and network meta-analysis. *Am J Geriatr Psychiatry*. 2024;32(12):1443-1465. doi:10.1016/j.jagp.2024.06.012

9. Woollacott M, Shumway-Cook A. Attention and the control of posture and gait: a review of an emerging area of research. *Gait Posture*. 2002;16(1):1-14. doi:10.1016/s0966-6362(01)00156-4

10. Khan MJ, Kannan P, Wong TWL, Fong KNK, Winser SJ. A systematic review exploring the theories underlying the improvement of balance and reduction in falls following dual-task training among older adults. *Int J Environ Res Public Health*. 2022;19(24):16890. doi:10.3390/ijerph192416890

11. Huang X, Zhao X, Li B, et al. Comparative efficacy of various exercise interventions on cognitive function in patients with mild cognitive impairment or dementia: a systematic review and network meta-analysis. *J Sport Health Sci*. 2022;11(2):212-223. doi:10.1016/j.jshs.2021.05.003

12. da Costa KG, Fontes EB, Menta A, et al. Prefrontal cortex oxygenation during exercise in older adults with motoric cognitive risk syndrome. *Adv Biol*. 2025;9(6):e2400231. doi:10.1002/adbi.202400231
13. Kwok MMY, Ng SSM, Myers J, So BCL. Aquatic high-intensity interval deep water running influence on cardiometabolic health and cognitive psychological responses in women. *Med Sci Sports Exercise*. 2024;56(11):2203-2210. doi:10.1249/MSS.0000000000003500
14. Montero-Odasso M, Verghese J, Beauchet O, Hausdorff JM. Gait and cognition: a complementary approach to understanding brain function and the risk of falling. *J Am Geriatr Soc*. 2012;60(11):2127-2136. doi:10.1111/j.1532-5415.2012.04209.x
15. Kim Y, Vakula MN, Waller B, Bressel E. A systematic review and meta-analysis comparing the effect of aquatic and land exercise on dynamic balance in older adults. *BMC GERIATRICS*. 2020;20(1):302. doi:10.1186/s12877-020-01702-9
16. Deng Y, Tang Z, Yang Z, et al. Comparing the effects of aquatic-based exercise and land-based exercise on balance in older adults: A systematic review and meta-analysis. *Eur Rev Aging Phys A*. 2024;21(1):13. doi:10.1186/s11556-024-00349-4
17. Campos DM, Ferreira DL, Gonçalves GH, Farche ACS, de Oliveira JC, Ansai JH. Effects of aquatic physical exercise on neuropsychological factors in older people: a systematic review. *Arch Gerontol Geriatr*. 2021;96:104435. doi:10.1016/j.archger.2021.104435
18. Li D, Chen P. Effects of Aquatic Exercise and Land-Based Exercise on Cardiorespiratory Fitness, Motor Function, Balance, and Functional Independence in Stroke Patients-A Meta-Analysis of Randomized Controlled Trials. *BRAIN SCIENCES*. 2021;11(8):1097. doi:10.3390/brainsci11081097
19. Parfitt R, Hensman MY, Lucas SJE. Cerebral blood flow responses to aquatic treadmill exercise. *Med Sci Sports Exercise*. 2017;49(7):1301-1308. doi:10.1249/MSS.0000000000001230
20. So BCL, Cheung HCY, Zheng YP, et al. Effect of moderate-intensity aquatic treadmill exercise on cognitive function and cerebral blood flow for healthy older adults. *Exp Gerontol*. 2024;197:112605. doi:10.1016/j.exger.2024.112605
21. Carter HH, Spence AL, Pugh CJA, Ainslie P, Naylor LH, Green DJ. Cardiovascular responses to water immersion in humans: Impact on cerebral perfusion. *Am J Physiol Regul Integr Comp Physiol*. 2014;306(9):R636-640. doi:10.1152/ajpregu.00516.2013
22. Tang Z, Wang Y, Liu J, Liu Y. Effects of aquatic exercise on mood and anxiety symptoms: A systematic review and meta-analysis. *FRONTIERS IN PSYCHIATRY*. 2022;13:1051551. doi:10.3389/fpsyt.2022.1051551
23. Carter HH, Pienaar O, Coleman A, et al. The effects of water temperature on cerebral blood flow during aquatic exercise. *Eur J Appl Physiol*. 2024;124(1):219-225. doi:10.1007/s00421-023-05264-7
24. Nasreddine ZS, Phillips NA, Bédirian V, et al. The Montreal cognitive assessment, MoCA: a brief screening tool for mild cognitive impairment. *J Am Geriatr Soc*. 2005;53(4):695-699. doi:10.1111/j.1532-5415.2005.53221.x
25. Schulz KF, Altman DG, Moher D, Consort Group. CONSORT 2010 statement: updated guidelines for reporting parallel group randomised trials. *BMJ*. 2010;340:c332.

doi:10.1136/bmj.c332
26. Podsiadlo D, Richardson S. The timed “up & go”: a test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc*. 1991;39(2):142-148. doi:10.1111/j.1532-5415.1991.tb01616.x
27. Plisky PJ, Gorman PP, Butler RJ, Kiesel KB, Underwood FB, Elkins B. The reliability of an instrumented device for measuring components of the star excursion balance test. *N Am j sports phys ther: NAJSPT*. 2009;4(2):92-99.
28. Jones CJ, Rikli RE, Beam WC. A 30-s chair-stand test as a measure of lower body strength in community-residing older adults. *Res Q Exerc Sport*. 1999;70(2):113-119. doi:10.1080/02701367.1999.10608028
29. Prieto TE, Myklebust JB, Hoffmann RG, Lovett EG, Myklebust BM. Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans Bio-Med Eng*. 1996;43(9):956-966. doi:10.1109/10.532130
30. Pinti P, Aichelburg C, Gilbert S, et al. A review on the use of wearable functional near-infrared spectroscopy in naturalistic environments. *Jpn Psychol Res*. 2018;60(4):347-373. doi:10.1111/jpr.12206
31. Scholkmann F, Kleiser S, Metz AJ, et al. A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology. *Neuroimage*. 2014;85 Pt 1:6-27. doi:10.1016/j.neuroimage.2013.05.004
32. Lehmann N, Kuhn YA, Keller M, et al. Balance training improves postural control and performance-related prefrontal brain activation in healthy older adults: results of a six-month randomized controlled training intervention. *Neurobiol Aging*. 2025;154:71-83. doi:10.1016/j.neurobiolaging.2025.07.001
33. Zimeo Morais GA, Balardin JB, Sato JR. fNIRS optodes’ location decider (fOLD): a toolbox for probe arrangement guided by brain regions-of-interest. *Sci Rep*. 2018;8(1):3341. doi:10.1038/s41598-018-21716-z
34. Brigadoi S, Cooper RJ. How short is short? Optimum source-detector distance for short-separation channels in functional near-infrared spectroscopy. *Neurophotonics*. 2015;2(2):25005. doi:10.1117/1.NPh.2.2.025005
35. Tachtsidis I, Scholkmann F. False positives and false negatives in functional near-infrared spectroscopy: issues, challenges, and the way forward. *Neurophotonics*. 2016;3(3):31405. doi:10.1117/1.NPh.3.3.031405
36. Fishburn FA, Ludlum RS, Vaidya CJ, Medvedev AV. Temporal derivative distribution repair (TDDR): a motion correction method for fNIRS. *Neuroimage*. 2019;184:171-179. doi:10.1016/j.neuroimage.2018.09.025
37. Baker WB, Parthasarathy AB, Busch DR, Mesquita RC, Greenberg JH, Yodh AG. Modified beer-lambert law for blood flow. *Biomed Opt Express*. 2014;5(11):4053-4075. doi:10.1364/BOE.5.004053
38. Pollonini L, Olds C, Abaya H, Bortfeld H, Beauchamp MS, Oghalai JS. Auditory cortex activation to natural speech and simulated cochlear implant speech measured with functional near-infrared spectroscopy. *Hear Res*. 2014;309:84-93. doi:10.1016/j.heares.2013.11.007
39. Stuart S, Alcock L, Rochester L, Vitorio R, Pantall A. Monitoring multiple cortical regions during walking in young and older adults: dual-task response and comparison

challenges. *Int J Psychophysiol: Off J Int Organ Psychophysiol*. 2019;135:63-72. doi:10.1016/j.ijpsycho.2018.11.006
40. Udina C, Avtzi S, Durduran T, et al. Functional near-infrared spectroscopy to study cerebral hemodynamics in older adults during cognitive and motor tasks: a review. *Front Aging Neurosci*. 2019;11:367. doi:10.3389/fnagi.2019.00367
41. Kahya M, Moon S, Ranchet M, et al. Brain activity during dual task gait and balance in aging and age-related neurodegenerative conditions: a systematic review. *Exp Gerontol*. 2019;128:110756. doi:10.1016/j.exger.2019.110756
42. Santosa H, Zhai X, Fishburn F, Huppert T. The NIRS brain AnalyzIR toolbox. *Algorithms*. 2018;11(5):73. doi:10.3390/a11050073
43. Lauenroth A, Ioannidis AE, Teichmann B. Influence of combined physical and cognitive training on cognition: a systematic review. *BMC Geriatr*. 2016;16:141. doi:10.1186/s12877-016-0315-1
44. Hao Y, Zhao Y, Luo H, Xie L, Hu H, Sun C. Comparative effectiveness of different dual task mode interventions on cognitive function in older adults with mild cognitive impairment or dementia: a systematic review and network meta-analysis. *Aging Clin Exp Res*. 2025;37(1):139. doi:10.1007/s40520-025-03016-5
45. Shariat A, Ghayour Najafabadi M, Ghannadi S, et al. Effects of aquatic therapy on balance in older adults: a systematic review and meta-analysis. *Eur Geriatr Med*. 2022;13(2):381-393. doi:10.1007/s41999-021-00577-2
46. Koechlin E, Basso G, Pietrini P, Panzer S, Grafman J. The role of the anterior prefrontal cortex in human cognition. *Nature*. 1999;399(6732):148-151. doi:10.1038/20178
47. Koechlin E, Hyafil A. Anterior prefrontal function and the limits of human decision-making. *Science*. 2007;318(5850):594-598. doi:10.1126/science.1142995
48. Okuda J, Fujii T, Ohtake H, et al. Differential involvement of regions of rostral prefrontal cortex (brodmann area 10) in time- and event-based prospective memory. *Int J Psychophysiol: Off J Int Organ Psychophysiol*. 2007;64(3):233-246. doi:10.1016/j.ijpsycho.2006.09.009
49. Ramnani N, Owen AM. Anterior prefrontal cortex: insights into function from anatomy and neuroimaging. *Nat Rev Neurosci*. 2004;5(3):184-194. doi:10.1038/nrn1343
50. Papegaaij S, Taube W, Baudry S, Otten E, Hortobágyi T. Aging causes a reorganization of cortical and spinal control of posture. *Front Aging Neurosci*. 2014;6:28. doi:10.3389/fnagi.2014.00028
51. Fujimoto H, Mihara M, Hattori N, et al. Cortical changes underlying balance recovery in patients with hemiplegic stroke. *Neuroimage*. 2014;85 Pt 1:547-554. doi:10.1016/j.neuroimage.2013.05.014
52. Hernandez-Sarabia JA, Schmid AA, Sharp JL, Stephens JA. Intervention-induced changes in balance and task-dependent neural activity in adults with acquired brain injury: a pilot randomized control trial. *Sens*. 2024;24(13):4047. doi:10.3390/s24134047
53. Neubauer AC, Fink A. Intelligence and neural efficiency. *Neurosci Biobehav Rev*. 2009;33(7):1004-1023. doi:10.1016/j.neubiorev.2009.04.001

54. Clark DJ. Automaticity of walking: functional significance, mechanisms, measurement and rehabilitation strategies. *Front Hum Neurosci*. 2015;9:246. doi:10.3389/fnhum.2015.00246
55. Holtzer R, Mahoney JR, Izzetoglu M, Izzetoglu K, Onaral B, Verghese J. fNIRS study of walking and walking while talking in young and old individuals. *J Gerontol A Biol Sci Med Sci*. 2011;66(8):879-887. doi:10.1093/gerona/glr068
56. de Rond V, D'Cruz N, Hulzinga F, et al. Neural correlates of weight-shift training in older adults: a randomized controlled study. *Sci Rep*. 2023;13(1):19609. doi:10.1038/s41598-023-46645-4
57. Byun K, Hyodo K, Suwabe K, et al. Mild exercise improves executive function with increasing neural efficiency in the prefrontal cortex of older adults. *GeroScience*. 2024;46(1):309-325. doi:10.1007/s11357-023-00816-3
58. Ono Y, Noah JA, Zhang X, et al. Motor learning and modulation of prefrontal cortex: an fNIRS assessment. *J Neural Eng*. 2015;12(6):66004. doi:10.1088/1741-2560/12/6/066004
59. Herold F, Wiegel P, Scholkmann F, Thiers A, Hamacher D, Schega L. Functional near-infrared spectroscopy in movement science: a systematic review on cortical activity in postural and walking tasks. *Neurophotonics*. 2017;4(4):41403. doi:10.1117/1.NPh.4.4.041403
60. Yu D, Li X, He S, Zhu H, Lam FMH, Pang MYC. The effect of dual-task training on cognitive ability, physical function, and dual-task performance in people with dementia or mild cognitive impairment: a systematic review and meta-analysis. *Clin Rehabil*. 2024;38(4):443-456. doi:10.1177/02692155231216621
61. Shoemaker LN, Wilson LC, Lucas SJE, Machado L, Thomas KN, Cotter JD. Swimming-related effects on cerebrovascular and cognitive function. *Physiol Rep*. 2019;7(20):e14247. doi:10.14814/phy2.14247
62. Menant JC, Maidan I, Alcock L, et al. A consensus guide to using functional near-infrared spectroscopy in posture and gait research. *Gait Posture*. 2020;82:254-265. doi:10.1016/j.gaitpost.2020.09.012
63. Maki BE, Holliday PJ, Topper AK. A prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. *J Gerontol*. 1994;49(2):M72-84. doi:10.1093/geronj/49.2.m72
64. Embrechts E, McGuckian TB, Rogers JM, et al. Cognitive and motor therapy after stroke is not superior to motor and cognitive therapy alone to improve cognitive and motor outcomes: new insights from a meta-analysis. *Arch Phys Med Rehabil*. 2023;104(10):1721-1734. doi:10.1016/j.apmr.2023.05.010
65. Silsupadol P, Shumway-Cook A, Lugade V, et al. Effects of single-task versus dual-task training on balance performance in older adults: A double-blind, randomized controlled trial. *Arch Phys Med Rehabil*. 2009;90(3):381-387. doi:10.1016/j.apmr.2008.09.559
66. Reliability of COP-based postural sway measures and age-related differences - ScienceDirect. Accessed June 28, 2026. https://www.sciencedirect.com/science/article/abs/pii/S0966636208000301
67. Maudsley-Barton S, McPheey J, Bukowski A, Leightley D, Yap MH. A

comparative study of the clinical use of motion analysis from kinect skeleton data. In: *2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. 2017:2808-2813. doi:10.1109/SMC.2017.8123052

68. Taylor ME, Lord SR, Delbaere K, Kurrle SE, Mikolaizak AS, Close JCT. Reaction time and postural sway modify the effect of executive function on risk of falls in older people with mild to moderate cognitive impairment. *Am J Geriatr Psychiatry: Off J Am Assoc Geriatr Psychiatry*. 2017;25(4):397-406. doi:10.1016/j.jagp.2016.10.010

69. T K, K F. Dominant side in single-leg stance stability during floor oscillations at various frequencies. *J Physiol Anthropol*. 2014;33(1):1-9. doi:10.1186/1880-6805-33-25

70. Sung PS, Lee D. Comparative analysis of dominant limb postural control in adults with and without fear of falling. *BMC Geriatr*. 2025;25(1):683. doi:10.1186/s12877-025-06258-0

71. Promsri A, Bangkomdet K, Jindatham I, Jenchang T. Leg dominance-surface stability interaction: effects on postural control assessed by smartphone-based accelerometry. *Sports (Basel)*. 2023;11(4):75. doi:10.3390/sports11040075

**Table 3. Postural Balance Outcomes in Exp and Ctrl Groups Before and After Intervention (mean ± SD)**

| Parameter | ACME (n = 10) | | AHIIT (n = 12) | | Group Effect | | Time Effect | | Group-Time Effect | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Pretraining | Posttraining | Pretraining | Posttraining | P Value | ηp² | P Value | ηp² | P Value | ηp² |
| **Parallel stance** | | | | | | | | | | |
| Sway Path Total (mm) | 423.7 ± 91.4 | 286.2 ± 58.8 | 489.6 ± 228.5 | 410.1 ± 163.6 | 0.1476 | 0.10 | 0.0001* | 0.53 | 0.2104 | 0.08 |
| Sway Velocity Total (mm/s) | 21.19 ± 4.57 | 14.31 ± 2.94 | 24.48 ± 11.42 | 20.84 ± 9.13 | 0.1477 | 0.10 | 0.0003* | 0.49 | 0.1830 | 0.09 |
| Max Amplitude A-P (mm) | 29.59 ± 11.40 | 21.85 ± 8.33 | 32.08 ± 13.89 | 33.61 ± 16.28 | 0.1814 | 0.09 | 0.2348 | 0.07 | 0.0480* | 0.18 |
| Max Amplitude M-L (mm) | 41.87 ± 13.15 | 14.24 ± 9.83 | 36.64 ± 47.25 | 31.38 ± 31.46 | 0.6265 | 0.01 | 0.0087* | 0.30 | 0.0486* | 0.18 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sway Area Total (mm²) | 1263 ± 523 | 473 ± 325 | 1651 ± 1787 | 1310 ± 1281 | 0.2263 | 0.07 | 0.0007* | 0.44 | 0.1171 | 0.12 |
| Sway Area Per Second (mm²/s) | 63.16 ± 26.18 | 23.67 ± 16.24 | 82.56 ± 89.36 | 65.98 ± 65.62 | 0.2248 | 0.07 | 0.0012* | 0.41 | 0.1275 | 0.11 |
| Area of 100% Ellipse (mm²) | 153.4 ± 100.8 | 52.5 ± 53.3 | 205.9 ± 364.3 | 168.7 ± 237.0 | 0.3788 | 0.04 | 0.0778 | 0.15 | 0.3839 | 0.04 |
| **Single-leg stance (left)** | | | | | | | | | | |
| Sway Path Total (mm) | 1768.8 ± 616.9 | 1017.0 ± 385.4 | 1440.1 ± 604.5 | 1099.6 ± 223.5 | 0.4676 | 0.03 | 0.0003* | 0.48 | 0.1104 | 0.12 |
| Sway Velocity Total (mm/s) | 88.45 ± 30.86 | 50.85 ± 19.27 | 58.47 ± 14.75 | 56.70 ± 9.62 | 0.1331 | 0.11 | <0.0001* | 0.60 | <0.0001* | 0.60 |
| Max Amplitude A-P (mm) | 106.93 ± 90.09 | 37.65 ± 16.85 | 69.09 ± 20.95 | 59.60 ± 17.85 | 0.6072 | 0.01 | 0.0075* | 0.31 | 0.0254* | 0.23 |
| Max Amplitude M-L (mm) | 150.34 ± 131.50 | 24.20 ± 19.08 | 87.45 ± 79.03 | 84.67 ± 41.78 | 0.9643 | 0.00 | 0.0088* | 0.30 | 0.0067* | 0.31 |
| Sway Area Total (mm²) | 21472 ± 31353 | 2976 ± 2429 | 7796 ± 6364 | 6801 ± 3484 | 0.3291 | 0.05 | 0.0536 | 0.17 | 0.0597 | 0.17 |
| Sway Area Per Second (mm²/s) | 1073.67 ± 1567.63 | 148.82 ± 121.46 | 389.85 ± 318.23 | 343.09 ± 189.81 | 0.3327 | 0.05 | 0.0546 | 0.17 | 0.0590 | 0.17 |
| Area of 100% Ellipse (mm²) | 2070.9 ± 3985.8 | 162.7 ± 166.2 | 774.4 ± 649.7 | 627.5 ± 369.5 | 0.5011 | 0.02 | 0.1062 | 0.13 | 0.1330 | 0.11 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Single-leg stance (right)** | | | | | | | | | | |
| Sway Path Total (mm) | 1397.5 ± 373.3 | 836.6 ± 322.2 | 1264.7 ± 397.5 | 1033.3 ± 206.9 | 0.7655 | 0.00 | 0.0006 * | 0.45 | 0.0975 | 0.13 |
| Sway Velocity Total (mm/s) | 69.89 ± 18.67 | 41.84 ± 16.12 | 63.24 ± 19.88 | 50.56 ± 11.87 | 0.8510 | 0.00 | 0.0005 * | 0.46 | 0.1207 | 0.12 |
| Max Amplitude A-P (mm) | 57.91 ± 21.63 | 36.29 ± 10.79 | 82.29 ± 37.47 | 64.33 ± 24.55 | 0.0175 * | 0.25 | 0.0005 * | 0.46 | 0.7068 | 0.01 |
| Max Amplitude M-L (mm) | 32.01 ± 7.77 | 25.25 ± 15.92 | 80.71 ± 64.12 | 60.01 ± 31.99 | 0.0106 * | 0.28 | 0.0612 | 0.16 | 0.3490 | 0.04 |
| Sway Area Total (mm²) | 5025 ± 2781 | 2096 ± 1128 | 7554 ± 5361 | 5292 ± 2985 | 0.0431 * | 0.19 | 0.0018 * | 0.39 | 0.6462 | 0.01 |
| Sway Area Per Second (mm²/s) | 251.23 ± 139.06 | 104.80 ± 56.41 | 377.67 ± 268.05 | 266.65 ± 144.49 | 0.0402 * | 0.19 | 0.0020 * | 0.39 | 0.6269 | 0.01 |
| Area of 100% Ellipse (mm²) | 215.0 ± 127.3 | 93.0 ± 54.8 | 514.9 ± 429.4 | 351.9 ± 198.0 | 0.0085 * | 0.30 | 0.0141 * | 0.27 | 0.7076 | 0.01 |

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**Supplementary Table 1. fNIRS channel layout and corresponding anatomical landmarks.**

| 10-10 System | Landmark (% of overlap) | Hemisphere |
|---|---|---|
| | ***Frontopolar*** | |
| Fp1–Fpz | FPC (BA 10) | L |
| Fpz–Fp2 | FPC (BA 10) | R |
| Fp1–AF3 | FPC (BA 10), DLPFC (BA 46) | L |
| AF3–AFz | FPC (BA 10), DLPFC (BA 9) | L |

| 10-10 System | Landmark (% of overlap) | Hemisphere |
|---|---|---|
| AFz–AF4 | FPC (BA 10), DLPFC (BA 9) | R |
| AF4–Fp2 | FPC (BA 10), DLPFC (BA 46) | R |
| | ***Prefrontal*** | |
| AF3–F3 | DLPFC (BA 9/46) | L |
| AF3–F1 | DLPFC (BA 9) | L |
| AFz–Fz | DLPFC (BA 9), pre-SMA (BA 8) | M |
| AF4–F2 | DLPFC (BA 9) | R |
| AF4–F4 | DLPFC (BA 9/46) | R |
| F5–F3 | DLPFC (BA 9/46), VLPFC (BA 45) | L |
| F3–F1 | DLPFC (BA 9/46) | L |
| F1–Fz | DLPFC (BA 9), pre-SMA (BA 8) | L |
| Fz–F2 | DLPFC (BA 9), pre-SMA (BA 8) | R |
| F2–F4 | DLPFC (BA 9/46) | R |
| F4–F6 | DLPFC (BA 9/46), VLPFC (BA 45) | R |
| | ***Frontocentral*** | |
| F5–FC5 | PMC (BA 6), VLPFC (BA 44/45) | L |
| F3–FC3 | DLPFC (BA 9), PMC (BA 6) | L |
| F1–FC1 | pre-SMA / PMC (BA 6/8) | L |
| Fz–FCz | pre-SMA / SMA (BA 6/8) | M |
| F2–FC2 | pre-SMA / PMC (BA 6/8) | R |
| F4–FC4 | DLPFC (BA 9), PMC (BA 6) | R |
| F6–FC6 | PMC (BA 6), VLPFC (BA 44/45) | R |
| FC5–FC3 | PMC (BA 6) | L |
| FC3–FC1 | PMC (BA 6) | L |
| FC1–FCz | SMA / PMC (BA 6) | L |
| FCz–FC2 | SMA / PMC (BA 6) | R |
| FC2–FC4 | PMC (BA 6) | R |
| FC4–FC6 | PMC (BA 6) | R |
| | ***Central*** | |
| FC5–C5 | PMC (BA 6), M1 (BA 4) | L |

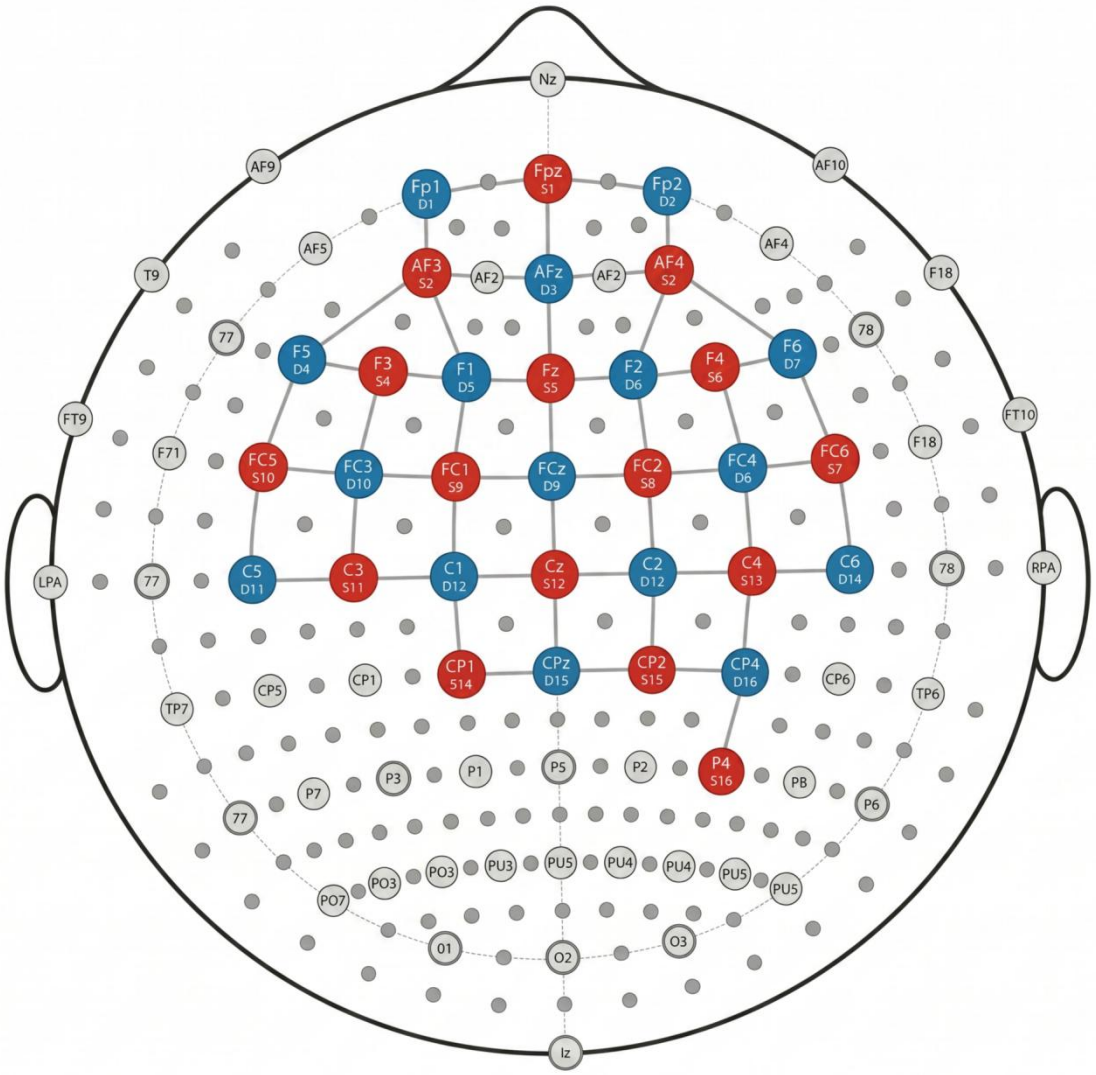
| 10-10 System | Landmark (% of overlap) | Hemisphere |
|---|---|---|
| FC3–C3 | PMC (BA 6), M1 (BA 4) | L |
| FC1–C1 | PMC (BA 6), M1 (BA 4) | L |
| FCz–Cz | SMA (BA 6), M1 (BA 4) | M |
| FC2–C2 | PMC (BA 6), M1 (BA 4) | R |
| FC4–C4 | PMC (BA 6), M1 (BA 4) | R |
| FC6–C6 | PMC (BA 6), M1 (BA 4) | R |
| C5–C3 | M1 (BA 4), S1 (BA 1/2/3) | L |
| C3–C1 | M1 (BA 4) | L |
| C1–Cz | M1 (BA 4), SMA (BA 6) | L |
| Cz–C2 | M1 (BA 4), SMA (BA 6) | R |
| C2–C4 | M1 (BA 4) | R |
| C4–C6 | M1 (BA 4), S1 (BA 1/2/3) | R |
| | ***Centroparietal*** | |
| C1–CP1 | S1 (BA 1/2/3), M1 (BA 4) | L |
| Cz–CPz | S1 (BA 1/2/3), SMA (BA 6) | M |
| C2–CP2 | S1 (BA 1/2/3), M1 (BA 4) | R |
| C4–CP4 | S1 (BA 1/2/3), SMG (BA 40) | R |
| CP1–CPz | S1 (BA 1/2/3), SPL (BA 5/7) | L |
| CPz–CP2 | S1 (BA 1/2/3), SPL (BA 5/7) | R |
| CP2–CP4 | S1 (BA 1/2/3), SMG (BA 40) | R |
| CP4–P4 | SPL (BA 7), AG (BA 39), SMG (BA 40) | R |

*Each channel is defined by an adjacent source–detector pair on the 10–10 EEG montage. The Landmark column lists the cortical structure(s) underlying the channel midpoint together with the percent overlap obtained from the fNIRS Optodes' Location Decider (fOLD) toolbox using the smoothed Colin27 brain template and the Brodmann atlas. Hemisphere: L = left, R = right, M = midline. Abbreviations: FPC = frontopolar cortex; DLPFC = dorsolateral prefrontal cortex; VLPFC = ventrolateral prefrontal cortex; PMC = premotor cortex; SMA = supplementary motor area; pre-SMA = pre-supplementary motor area; M1 = primary motor cortex; S1 = primary somatosensory cortex; SPL = superior parietal lobule; SMG = supramarginal gyrus; AG = angular gyrus; BA = Brodmann area.*

**Supplementary Table 2. Exploratory Functional-Region HbO Concentrations in ACME and AHIIT Groups by Stance Condition (mean ± SD)**

| Brain Region | ACME (n = 10) | | AHIIT (n = 12) | | Group Effect | | Time Effect | | Group-Time Effect | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pretraining | Posttraining | Pretraining | Posttraining | P Value | ηp² | P Value | ηp² | P Value | Holm P | ηp² |
| **Parallel stance** | | | | | | | | | | | |
| Prefrontal cognitive-control region | -2.19 ± 1.60 | 0.35 ± 2.18 | 1.24 ± 4.60 | -0.03 ± 1.54 | 0.0383 * | 0.20 | 0.6500 | 0.01 | 0.0738 | 0.3691 | 0.15 |
| Motor and sensorimotor control region | -0.25 ± 0.67 | 0.81 ± 2.08 | 0.01 ± 0.69 | 0.62 ± 0.69 | 0.9163 | 0.00 | 0.0208 * | 0.24 | 0.4958 | 1.0000 | 0.02 |
| **Single-leg stance (left)** | | | | | | | | | | | |
| Prefrontal cognitive-control region | 4.55 ± 8.45 | 0.13 ± 3.69 | 0.93 ± 2.73 | 1.17 ± 3.07 | 0.3731 | 0.04 | 0.2342 | 0.07 | 0.1452 | 0.5807 | 0.10 |
| Motor and sensorimotor control region | 1.05 ± 3.31 | 0.47 ± 3.55 | 0.78 ± 1.88 | 1.40 ± 2.52 | 0.6029 | 0.01 | 0.9474 | 0.00 | 0.5694 | 1.0000 | 0.02 |
| **Single-leg stance (right)** | | | | | | | | | | | |
| Prefrontal cognitive-control region | 5.93 ± 6.51 | -0.24 ± 5.22 | 1.21 ± 3.19 | 0.61 ± 2.66 | 0.2164 | 0.08 | 0.0161 * | 0.26 | 0.0305 * | 0.1829 | 0.21 |
| Motor and sensorimotor control region | 1.91 ± 1.79 | 0.62 ± 2.29 | 0.57 ± 1.38 | 0.33 ± 1.75 | 0.1602 | 0.10 | 0.1919 | 0.08 | 0.3358 | 1.0000 | 0.05 |

*Values are presented as mean ± SD in HbO (×10⁻⁷ mol/L). The prefrontal cognitive-control region represents the participant-level mean of the frontopolar and prefrontal ROIs; the motor and sensorimotor control region represents the participant-level mean of the frontocentral, central, and centroparietal ROIs. *Unadjusted or Holm-adjusted $P < 0.05$, as indicated. Holm adjustment was applied across the six Group × Time tests.*




**Supplementary Figure 1. fNIRS optode montage and scalp locations based on the international 10–10 system**

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryFigure1.tif
- SupplementaryTable1.docx
- SupplementaryTable2.docx