Research Square

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Balance function and cortical activation patterns following speed- and duration-adapted robotic exoskeleton training in people with subacute stroke

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Abstract

Background

Robotic exoskeleton training (RET) parameters in stroke rehabilitation exhibit variability, highlighting the need for optimization to improve therapeutic efficacy. This study quantified the effects of speed- and duration-adapted RET on balance function and cortical activation patterns in people with subacute stroke and explored the associated neurophysiological mechanisms.

Methods

Sixty participants were randomized into four groups using a 2 x 2 factorial design (speed: 0.2 m/s vs. 0.5 m/s; duration: 20 min vs. 50 min), training 5 days/week for 3 weeks. Outcome measures included the Berg Balance Scale (BBS), Timed Up and Go Test (TUGT) and cortical activation indices assessed using functional near-infrared spectroscopy (fNIRS), including changes in oxygenated hemoglobin concentration (ΔHbO_2) and laterality index (LI) in the primary motor cortex (M1), premotor cortex/supplementary motor area (PMC/SMA), and dorsolateral prefrontal cortex (DLPFC).

Results

All groups exhibited significant improvements in BBS and TUGT scores after the intervention. Compared with the low-speed / short-duration group, the high-speed / long-duration and low-speed / long-duration group showed significantly greater improvements in BBS scores, with no significant TUGT differences. Analysis of cortical activation indices analysis revealed that the high-speed / long-duration group exhibited significantly increased ΔHbO_2 in the affected M1 (A-M1), and more symmetrical interhemispheric activation pattern in the $LI_{PMC/SMA}$ and LI_{DLPFC}. Correlation analysis confirmed that improvements in BBS scores were significantly positively correlated with $\Delta HbO_{2\ A-PMC/SMA}$ and negatively correlated with changes in $LI_{PMC/SMA}$ recovery.

Conclusion

Combining higher speed and longer duration in RET may promote balance recovery and is associated with changes in cortical activation patterns. These findings provide preliminary evidence for optimizing RET parameters and offer a potential neurophysiological basis for personalized stroke rehabilitation.

Introduction

Lower-limb motor dysfunction is a common sequela of subacute stroke, severely compromising patients' walking ability and quality of life [1–3]. In recent years, lower-limb robotic exoskeleton training (RET) has emerged as a promising rehabilitation training, owing to its capacity to provide repetitive, quantifiable, and task-specific gait training[4–6]. Studies have demonstrated that RET can improve overall walking performance in people with subacute stroke compared to conventional rehabilitation [7, 8]. However, current

research primarily focuses on validating the overall efficacy of RET, paying insufficient attention to the systematic optimization of key training parameters, such as walking speed and session duration, remains a key challenge in rehabilitation engineering[9]. The lack of standard parameter selection limits the potential for further enhancing rehabilitation outcomes and developing personalized protocols.

Gait is a complex neurologically controlled process involving the coordinated regulation of multi-regional brain networks [10]. Post-stroke recovery of lower-limb function is closely associated with the remodeling of cortical activation patterns [9, 11, 12]. Therefore, elucidating how different RET parameters influence cortical activation patterns is key to understanding their mechanisms of action and achieving precise rehabilitation. Functional near-infrared spectroscopy (fNIRS), as a non-invasive brain imaging technique, offers a unique advantage for investigating these mechanisms by enabling real-time monitoring of cortical hemodynamic responses with relatively high temporal resolution during natural movements such as walking [13–15].

Based on this rationale, this study employs a randomized controlled trial design to quantitatively analyze the effects of different lower-limb RET regimens—varying in walking speed (conventional vs. high) and session time (conventional vs. long duration)—on balance function and cortical activation patterns in people with subacute stroke. The core innovation of this research lies in the synchronous integration of fNIRS neuroimaging, aiming to: (1) assess the differential modulation of activation patterns in motor-related brain areas (e.g., primary motor cortex, premotor/supplementary motor area, and prefrontal cortex) by different parameter regimens; and (2) explore associations between cortical activation changes and clinical outcomes. These findings may provide neurophysiological evidence to inform the optimization of RET parameters and the development of individualized stroke rehabilitation strategies.

Methods

Study Design and Participants

This was an assessor-blinded, parallel-group randomized clinical trial was conducted and reported in accordance with the CONSORT 2025 guidelines. The study aimed to evaluate the effects of different gait training regimens on cortical hemodynamic responses in people with subacute stroke. The study protocol was approved by the Medical Ethics Committee of Shanghai Yangzhi Rehabilitation Hospital (Shanghai Sunshine Rehabilitation Center), No. (2023-075).

A total of 60 hospitalized patients with subacute stroke were enrolled in this study at Yangzhi Rehabilitation Hospital, affiliated with Tongji University, between January and November 2024. The inclusion criteria were as follows: (1) diagnosis of stroke confirmed by cranial CT or MRI imaging, including cerebral infarction and cerebral hemorrhage, with a duration of 2 weeks to 6 months after onset; (2) stable vital signs, stable condition, post-stroke hemiplegia, and gait disorder; (3) age 18–80 years, weight ≤ 100kg; (4) Functional Ambulation Category (FAC) scale grade ≥ 2 (Grade 2: the ability to walk with continuous or intermittent physical support from one assistant), and able to walk with intermittent assistance from one person for at least 15 meters; (6) good cognitive function, who understood and actively participated in the training protocol, agreed to and signed the informed consent form. The study's exclusion criteria include: (1) Severe limitation of joint range of motion that restricts walking; (2) unhealed fracture or severe osteoporosis; (3)

skin damage or infection of the lower limbs or other body parts where the exoskeleton is worn;(4) unstable angina pectoris, severe arrhythmia and other heart diseases; (5) severe chronic obstructive pulmonary disease; (6) untreated deep vein thrombosis; (7) participated in other clinical trials during the same period.

Participants were randomly assigned using a simple randomization procedure. A random allocation sequence for 60 participants was generated in a 1:1:1:1 ratio via SPSS software (version 27.0), and the random seed was documented. The random allocation sequence was generated by an independent statistician who was not involved in participant enrollment or intervention delivery. Allocation concealment was achieved using sealed, opaque envelopes containing assignment numbers. Based on the numbered sequence, the treating therapists assigned participants to one of the four training groups in a 2 (Speed) × 2 (Time) factorial design:

·Group T1S1 (Low Speed/Short Duration): 0.2 m/s for 20 minutes.

·Group T1S2 (High Speed/Short Duration): 0.5 m/s for 20 minutes.

·Group T2S1 (Low Speed/Long Duration): 0.2 m/s for 50 minutes.

·Group T2S2 (High Speed/Long Duration): 0.5 m/s for 50 minutes.

All participants received a 40-minute session of standardized conventional rehabilitation therapy, followed by their assigned RET. Robotic exoskeleton training was carried out using an over-ground wearable exoskeleton (The UGO220, Hangzhou Chengtian Technology Development Co., China) under the supervision of a trained physiotherapist (Fig. 1A). Training was conducted five sessions per week for three consecutive weeks (15 sessions in total).

Functional Outcome Measures

The primary functional outcome measures were assessed using the Berg Balance Scale (BBS) to evaluate postural balance and the Timed Up and Go Test (TUGT) to assess functional mobility stability.

BBS

This 14-item scale assesses static and dynamic balance abilities. Each item is scored from 0 to 4, with a maximum total score of 56. Higher scores indicate better balance function, and scores below 40 signifies a high risk of falls.

TUGT: Participants are seated in a chair with a backrest (seat height: 45 cm), with a marker placed on the floor 3 meters in front of the chair. Upon hearing the command “Go”, participants stand up, walk forward to the marker once steady on their feet, then turn around and return to sit back down in the chair. Participants were instructed to complete the entire process as quickly as possible, and test time is recorded in seconds. This test is performed three times, and the final result is the average of the three trials. During the test, a researcher must be present to ensure the participants’ safety without providing physical assistance.

fNIRS Data Acquisition and Preprocessing

Cortical hemodynamic activity was monitored using a portable, research-grade fNIRS system (NirScan-500c, HuiChuang Medical Equipment Co., Ltd., China) with a 61-channel configuration (Fig. 1A). Each channel consisted of a light source emitting at three wavelengths (730, 808, and 850 nm) and a detector, enabling the measurement of relative changes in oxygenated hemoglobin (ΔHbO_2).

The experimental paradigm is illustrated in Fig. 1B. Participants began with a 60-second static standing period for baseline measurement, followed by four repeated cycles of 40 seconds of walking and 60 seconds of rest. During fNIRS measurements, participants wore the 61-channel cap while seated comfortably (Fig. 1C). Channel positions were co-registered to the MNI standard brain template using the NirSpace software (HuiChuang Medical Equipment). The cap was positioned with the Cz location at the intersection of channels CH30, CH32, CH36, and CH42, and the Fz location at the midpoint of CH6 and CH57. The regions of interest (ROIs) included the primary motor cortex (M1), premotor cortex/supplementary motor area (PMC/SMA), and dorsolateral prefrontal cortex (DLPFC) in both hemispheres. The corresponding channels were as follows: left hemisphere, DLPFC (CH5, CH6), PMC/SMA (CH26, CH29, CH30), and M1 (CH31, CH32); right hemisphere, DLPFC (CH57, CH58), PMC/SMA (CH36, CH55, CH56), and M1 (CH42, CH44).

Raw fNIRS data were sampled at 11 Hz and preprocessed using the NirSpark software (v1.8.1, HuiChuang Medical Equipment). The preprocessing pipeline included: (1) conversion of raw light intensity to optical density; (2) correction of motion artifacts using a spline interpolation algorithm; (3) band-pass filtering (0.01–0.2 Hz) to remove physiological noise and slow drifts; (4) conversion of optical density to relative concentration changes of HbO_2 based on the modified Beer-Lambert law. The ΔHbO_2 signal was selected as the primary indicator of hemodynamic response due to its higher sensitivity to regional cerebral blood flow.

Cortical Activation and Lateralization Analysis

For each trial, the average ΔHbO_2 concentration during a 20-second task period (0-20s after gait onset) was calculated relative to a 2-second pre-task baseline. Cortical activation was assessed using ΔHbO_2 in the affected (A-) and unaffected (U-) hemispheres [16]. Interhemispheric activation asymmetry was quantified using the Laterality Index (LI), calculated as follows[17]:

$LI = (\Delta HbO_2_U - \Delta HbO_2_A) / (\Delta HbO_2_U + \Delta HbO_2_A)$.

The LI ranges from − 1 to 1. A positive LI indicates activation in the unaffected hemisphere, whereas a negative LI indicates greater activation in the affected hemisphere, and an LI value closer to 0 indicates a more symmetrical activation pattern. An absolute LI value > 0.2 was defined as significant interhemispheric asymmetry [17].

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics (Version 27.0). MATLAB (MathWorks, Natick, MA, USA) was used for the visualization of fNIRS-derived cortical hemodynamic responses, including

the generation of topographic maps of ΔHbO_2changes. The normality of continuous variables was assessed using the Shapiro-Wilk test. Baseline characteristics across the four groups were compared as follows: categorical variables using the chi-square test, and continuous variables using one-way analysis of variance (ANOVA) for normally distributed data or the Kruskal-Wallis H test for non-normally distributed data. To evaluate the intervention effects, within-group differences (pre- vs. post-training) for functional and cortical metrics were analyzed using paired t-tests (for normal data) or Wilcoxon signed-rank tests (for non-normal data). Between-group differences in the magnitude of change (post-pre) were examined using analysis of covariance (ANCOVA), adjusting for baseline scores, or the Kruskal-Wallis H test, as appropriate. If a significant main effect was found, post-hoc pairwise comparisons were conducted with Bonferroni correction. Furthermore, Spearman's rank correlation analysis was employed to explore the relationships between improvements in lower-limb function and changes in cortical activation. The correlation strength was interpreted as follows: high ($|r| \geq 0.5$), moderate ($0.3 \leq |r| < 0.5$), or low ($0.1 \leq |r| < 0.3$). The significance level (α) was set at 0.05 for all tests.

Results

Participant Flow and Baseline Characteristics

The participant flow diagram is presented in Fig. 2. Sixty eligible people with subacute stroke were randomly assigned to four groups (n = 15 per group). After the 15-session intervention, complete pre- and post-training data were collected from 58 participants. Two participants in the T2S1 group withdrew from the study due to early discharge. As shown in Table 1, no significant differences were observed in baseline characteristics, including gender, age, stroke duration, stroke type, hemiplegic side, and Functional Ambulation Category (FAC) scores (all $p > 0.05$).

Table 1
Baseline Characteristics of Study Participants

Sex,(Male/Female)	**T1S1 (n = 15)**	**T1S2 (n = 15)**	**T2S1 (n = 13)**	**T2S2 (n = 15)**	**F/H/x^2**	**p**
	12/3	**12/3**	**11/2**	**12/3**	**0.140**	**0.987[a]**
Age (years)	54.93 ± 14.24	56.33 ± 10.60	56.40 ± 14.09	52.20 ± 13.17	0.198	0.897[b]
Duration (days)	81.60 ± 50.46	77.60 ± 44.88	90.53 ± 40.92	111.67 ± 41.28	1.747	0.168[b]
Stroke type (Ischemic/Hemorrhagic)	11/4	9/6	8/5	9/6	0.807	0.848[a]
Hemiplegic Side (Left/Right)	6/9	4/11	2/11	7/8	5.066	0.167[a]
FAC grade	3(2,3)	3(2,4)	3(2,3)	2(2,3)	4.952	0.175[c]

T1S1: routine walking training group; T1S2: high-speed walking training group; T2S1: long-time walking training group; T2S2: high-speed long-time walking training group; FAC: Functional Ambulation Category.

a: Analyzed using Pearson's chi-square test;

b: Analyzed using one-way ANOVA;

c: Analyzed using the Kruskal–Wallis H test.

Effects on Functional Outcomes

The within- and between-group comparisons for functional outcomes are summarized in Table 2. A significant between-group difference was observed in BBS scores ($F = 5.393$, $p < 0.05$, $\eta^2=0.244$). Post hoc analyses indicated that the T2S1 and T2S2 groups showed significantly greater improvements than the T1S1 group ($p < 0.05$). All groups demonstrated significant within-group improvements in both BBS and TUGT after the intervention ($p < 0.05$).

Table 2
Comparison of BBS and TUGT in four groups of patients

Index	Group	Pre-intervention	Post-intervention	Mean difference (95%CI)	t	p
BBS	T1S1	39.27 ± 11.11	42.13 ± 10.58	2.87(2.12 ~ 3.62)***	8.189	<0.001
	T1S2	40.73 ± 9.29	44.20 ± 9.21	3.47(2.66 ~ 4.27)***	9.213	<0.001
	T2S1	32.62 ± 5.88	37.00 ± 7.06 †	4.38(3.16 ~ 5.61)***	7.817	<0.001
	T2S2	34.93 ± 8.38	40.07 ± 8.82 ††	5.13(4.03 ~ 6.24)***	9.964	<0.001
	F	5.393				
	P	0.003				
	η	0.244				
TUGT	T1S1	41.26 ± 14.56	36.61 ± 16.41	-4.65(-8.50~-0.08)*	-2.592	0.021
	T1S2	39.56 ± 13.16	33.84 ± 12.36	-5.71(-8.60~-2.83)***	-4.243	<0.001
	T2S1	59.19 ± 26.38	48.13 ± 23.99	-11.07(-15.33~-6.80)***	-5.651	<0.001
	T2S2	45.51 ± 13.64	35.40 ± 14.90	-10.10(-12.50~-7.70)***	-9.031	<0.001
	F	2.538				
	P	0.067				
	η	0.132				

* indicates statistically significant differences between intervention groups ($p < 0.05$); ** indicates $p < 0.01$; *** indicates $p < 0.001$.† indicates statistically significant differences compared to the T1S1 group ($p < 0.05$); †† indicates $P < 0.01$; ††† indicates $p < 0.001$.

Effects on Cortical Activation

The cortical hemodynamic responses and lateralization indices across groups are quantified in Fig. 3, and the topological mapping of ΔHbO_2 concentration changes across the four intervention groups is presented in Fig. 4.

M1

A significant between-group difference was found in changes in ΔHbO_2 in the affected M1 ($H = 8.853$, $p < 0.05$). The T2S2 (high speed/long duration) group showed a significantly greater increase in ΔHbO_2

compared to the T1S1 group ($p < 0.05$). Significant within-group increases in ΔHbO_2 were observed in both the affected and unaffected M1 in the T2S2 group ($p < 0.05$). Furthermore, significant within-group changes in LI_{M1} were observed in the T1S2 and T2S2 groups ($p < 0.05$).

PMC/SMA

A significant between-group difference was found in $LI_{PMC/SMA}$ ($H = 13.092$, $p < 0.05$). Post-hoc tests indicated that the T1S2 and T2S2 groups achieved significantly greater improvements in LI than the T1S1 group ($p < 0.05$). All groups showed significant within-group increases in $\Delta HbO_{2\ PMC/SMA}$ ($p < 0.05$). Additionally, the T1S2 and T2S2 groups exhibited significant within-group increases in $\Delta HbO_{2\ A-PMC/SMA}$ and $LI_{PMC/SMA}$ ($p < 0.05$).

DLPFC

A significant between-group difference was observed in LI_{DLPFC} ($H = 10.905$, $p < 0.05$), with the T2S2 group showing significantly greater change than the T1S1 group ($p < 0.05$). The T1S2 and T2S2 groups demonstrated significant within-group increases in bilateral $\Delta HbO_{2\ DLPFC}$ and LI_{DLPFC} ($p < 0.05$). The T2S1 group also showed a significant within-group improvement in LI_{DLPFC}($p < 0.05$).

Correlation between Functional Improvement and Cortical Activation

Improvements in BBS scores were positively correlated with changes in $\Delta HbO_{2\ PMC/SMA}$ ($r = 0.260$, $p < 0.05$) and negatively correlated with changes in $LI_{PMC/SMA}$ ($r=-0.305$, $p < 0.05$) (Fig. 5).

Discussion

This study investigated the effects of different speed- and duration-adapted robotic exoskeleton training (RET) regimens on balance function and cortical activation patterns in people with subacute stroke. All groups showed significant improvements in BBS and TUGT scores after the intervention. Compared with the low-speed/short-duration group (T1S1), both the long-duration groups (T2S1 and T2S2) demonstrated greater improvements in BBS scores, whereas no significant between-group differences were observed in TUGT outcomes. These findings suggest that longer training duration may contribute to balance recovery, while the effects on functional mobility remain less evident. In addition, different training regimens were associated with distinct cortical activation patterns, and changes in PMC/SMA activation were correlated with improvements in balance function.

Cortical activation patterns play an important role in post-stroke motor recovery[18], particularly in relation to the asymmetrical motor control associated with hemiplegic gait [19–21]. Previous studies have suggested that changes in interhemispheric activation may reflect functional reorganization during stroke recovery [22, 23]. Consistent with this perspective, our fNIRS findings revealed increased cortical hemodynamic responses in motor-related regions, including M1, PMC/SMA, and DLPFC, with changes varying across training regimens. Significant changes in the LI were also observed, suggesting alterations in interhemispheric

activation patterns following RET. These responses may be related to the repetitive and coordinated sensorimotor input provided by exoskeleton-assisted walking, which could facilitate proprioceptive processing and cortical sensorimotor integration [24]. However, the observed hemodynamic changes should be interpreted as indirect indicators of cortical activity rather than direct evidence of neural reorganization.

The differential cortical responses across training regimens suggest that walking speed and session duration may influence motor control through different neurophysiological processes. Although prolonged low-speed training (T2S1) improved balance function, it was associated with relatively limited changes in cortical activation indices compared with the high-speed groups. One possible explanation is that repetitive rhythmic walking may place greater demands on automatic locomotor control mechanisms, including spinal central pattern generators (CPGs)[25, 26], which contribute to rhythmic stepping and locomotor coordination [27]. In contrast, higher-speed training (T1S2 and T2S2) was associated with more pronounced changes in PMC/SMA and DLPFC activation patterns. Faster walking may increase demands on motor planning, postural adjustment, and executive control, particularly in individuals with impaired locomotor automaticity after stroke [18, 28–32]. Consistent with this interpretation, Kim et al. reported greater motor-related cortical activation during faster RET than during self-selected-speed training in healthy individuals [33]. These findings suggest that training speed may influence cortical engagement; however, the potential involvement of CPG-mediated control remains hypothetical because subcortical and spinal neural activity was not directly assessed.

Notably, the high-speed/long-duration group (T2S2) demonstrated a significantly greater increase in ΔHbO_2in the affected M1 than the T1S1 group. Given the important role of M1 in motor learning and adaptive plasticity [34–36], this finding suggests that combining higher walking speed with longer training duration may facilitate cortical engagement in the affected hemisphere. Nevertheless, a synergistic interaction between speed and duration cannot be established without a significant interaction effect. Furthermore, improvements in BBS scores were positively correlated with changes in PMC/SMA ΔHbO_2 ($r = 0.260$) and negatively correlated with changes in PMC/SMA LI ($r = -0.305$). The PMC/SMA contributes to motor planning, movement sequencing, and locomotor regulation [37–39], and changes in its activation patterns may therefore be associated with improved balance control. These associations are consistent with the potential involvement of cortical functional adaptation in motor recovery [40], although they do not establish a causal relationship between cortical activation and functional improvement.

Several limitations should be acknowledged. First, the 3-week intervention period and lack of follow-up assessment preclude conclusions about the long-term sustainability of functional improvements and cortical activation changes. Second, the exoskeleton's maximum walking speed (0.5 m/s) restricted the investigation to two speed levels, limiting the characterization of a broader dose–response relationship. In addition, fNIRS measures cortical hemodynamic responses indirectly and cannot directly assess the contribution of subcortical or spinal locomotor networks. Future studies should incorporate larger samples, broader training parameter ranges, longer follow-up periods, and complementary neurophysiological measures.

Conclusion

This study provides neurophysiological evidence to inform the optimization of robotic exoskeleton training regimens in people with subacute stroke. Our findings suggest that different training parameters are associated with distinct cortical activation patterns and that improvements in balance function are correlated with changes in cortical activation and interhemispheric lateralization, particularly in the PMC/SMA. These findings may contribute to the development of more individualized and effective exoskeleton-assisted stroke rehabilitation strategies.

Declarations

Ethics approval and consent to participate

The study protocol was approved by Medical Ethics Committee of Shanghai Yangzhi Rehabilitation Hospital (Shanghai Sunshine Rehabilitation Center), No. (2023-075).

Informed consent

Informed consent was obtained from all subjects involved in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no conflicting interests.

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Author Contribution

Q.Q. were responsible for resources and funding acquisition. Conceptualization was performed by J.C.Y., Y.P., X.L.L., and Q.Q. J.C.Y. contributed to the writing of the original draft. Methodology was designed by J.C.Y., J.H.L., and Y.X.Z. Investigation was conducted by J.H.L., X.W.L., X.W.H, and Y.X.Z. Formal analysis,

visualization, and data curation were carried out by J.C.Y, J.H.L, and Y.X.Z. Supervision was provided by J.H.L., Y.X.Z., X.W.L., and X.W.H. Project administration was managed by Y.P., and X.L.L. J.H.L. and Y.X.Z. contributed to writing – review and editing, and validation was performed by X.W.L.,and Y.P.J.C.Y., J.H.L. and Y.X.Z. contributed equally to this work.

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Availability of data and materials

The data that support the findings of this investigation are accessible upon request from the corresponding author.

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Figures

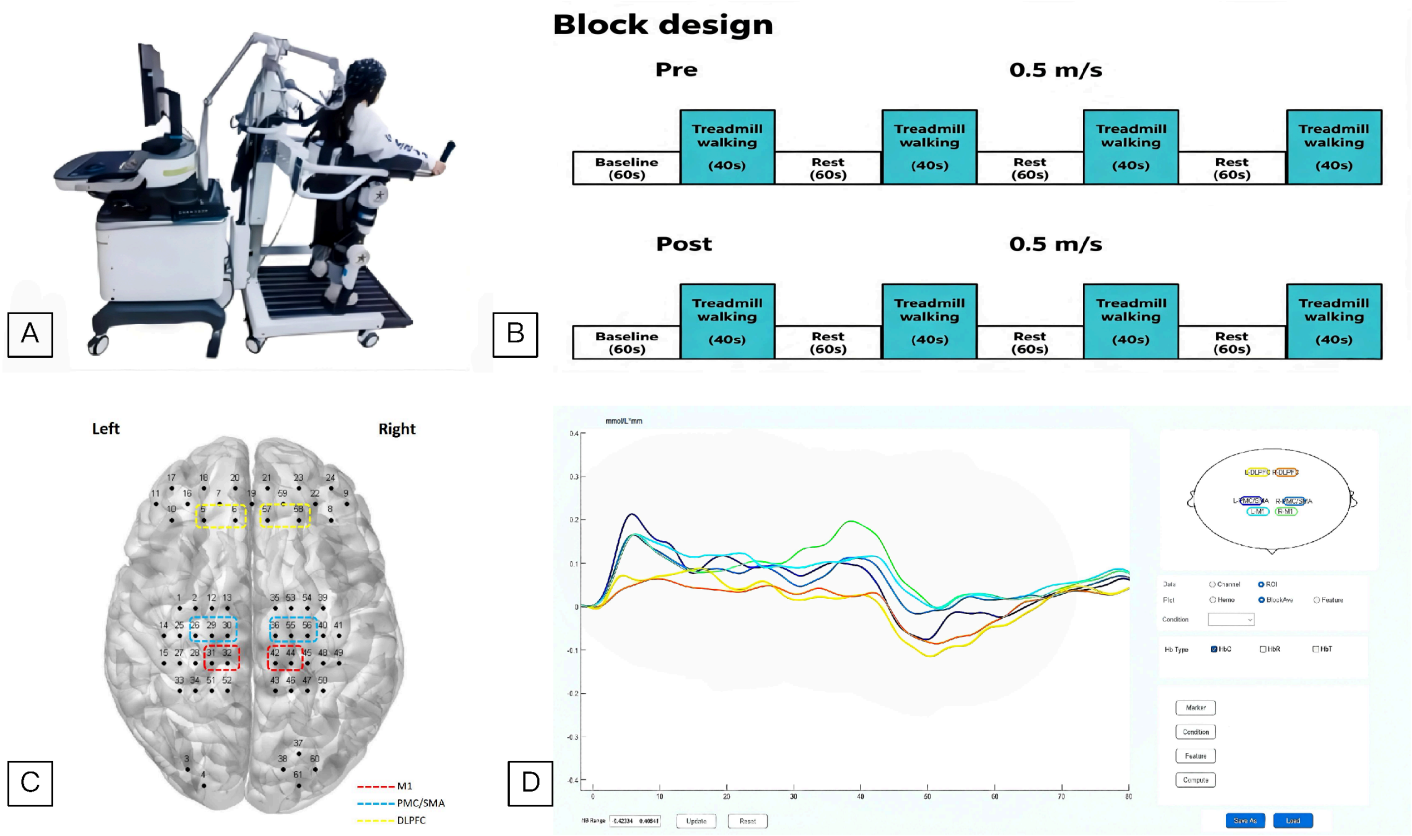


Figure 1

Brain cortex activation experiment

Note: (A) Brain cortex activation experiment diagram; (B) Block paradigm design; (C) Related brain regions and channel arrangement diagram; (D) NirSpark software preprocessing interface

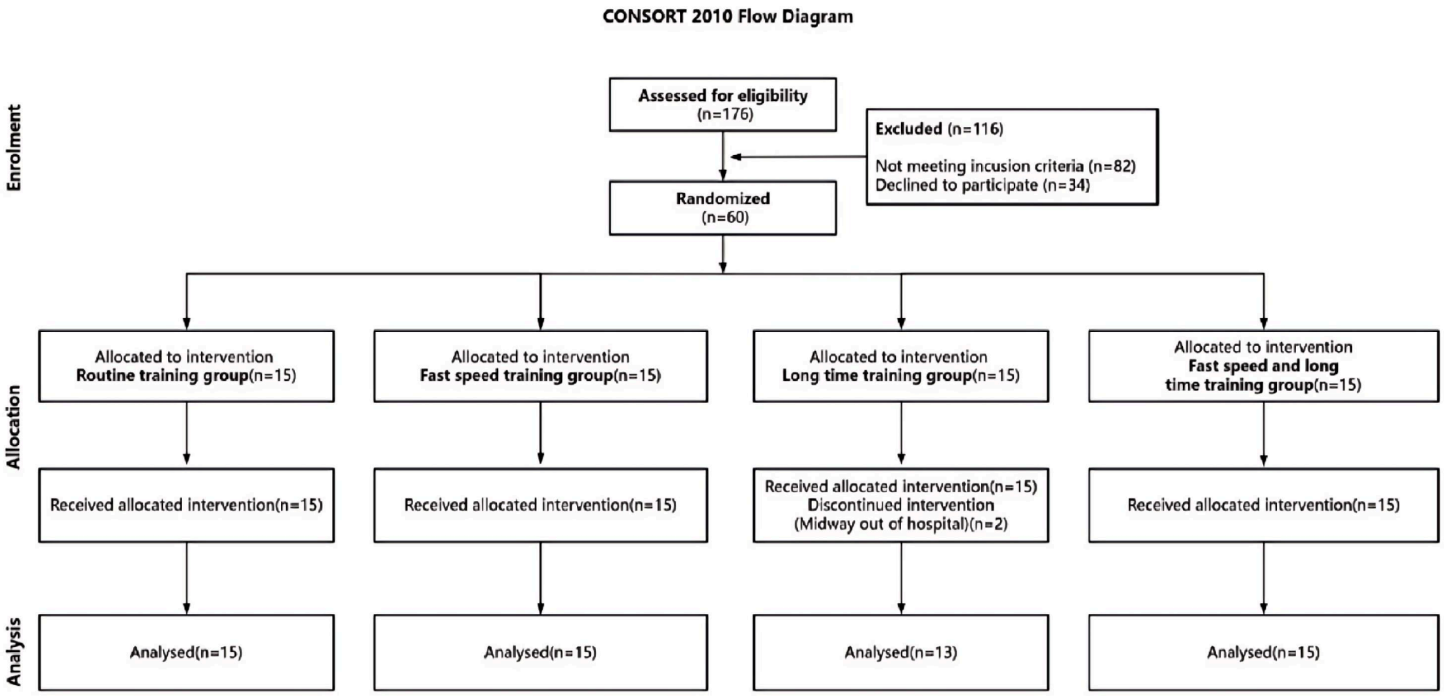


Figure 2

CONSORT flow diagram.

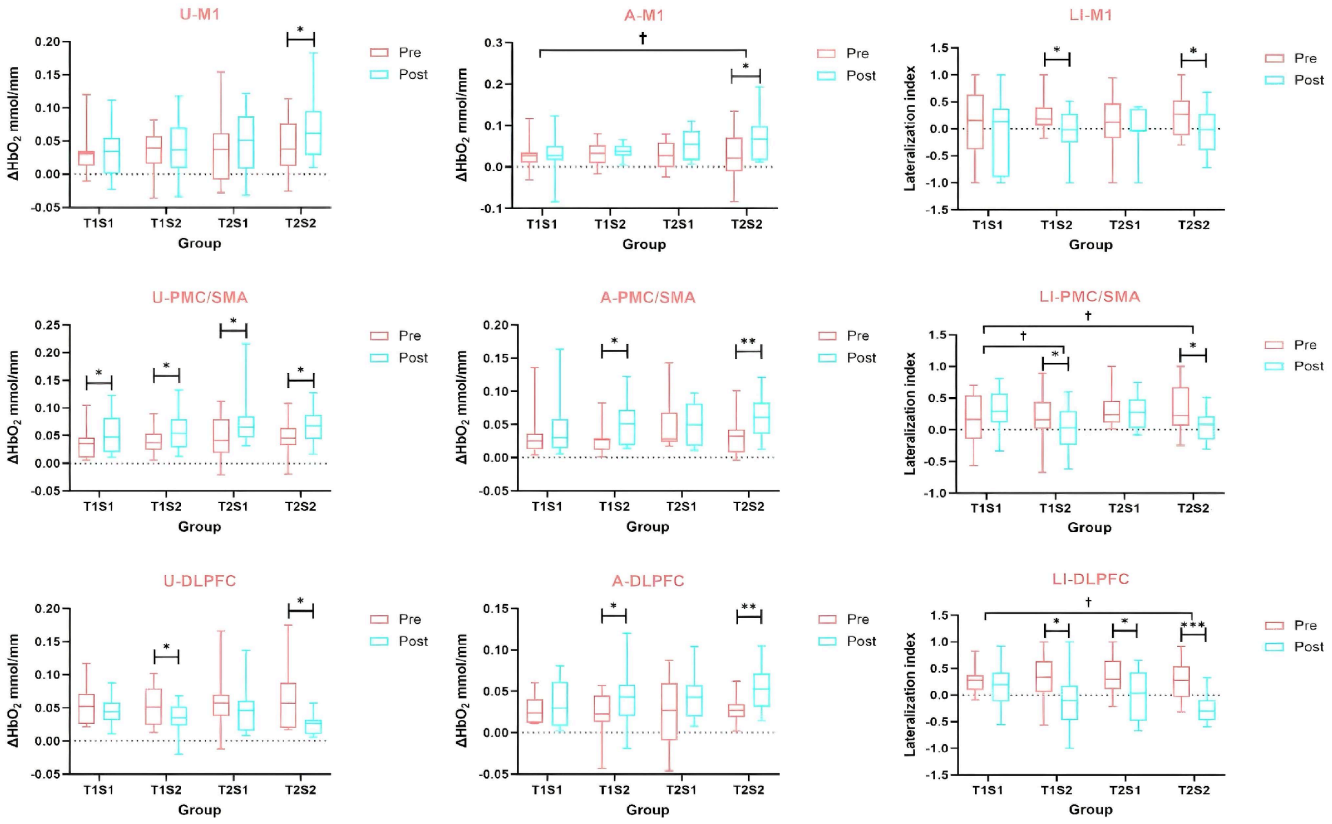


Figure 3

Activation and lateralization of cerebral cortex

* indicates statistically significant differences between intervention groups (p<0.05); ** indicates p<0.01; *** indicates p<0.001.† indicates statistically significant differences compared to the T1S1 group (p<0.05); †† indicates P<0.01; ††† indicates p<0.001. U-indicates the unaffected side; A-indicates the affected side; LI-indicates the lateralization.

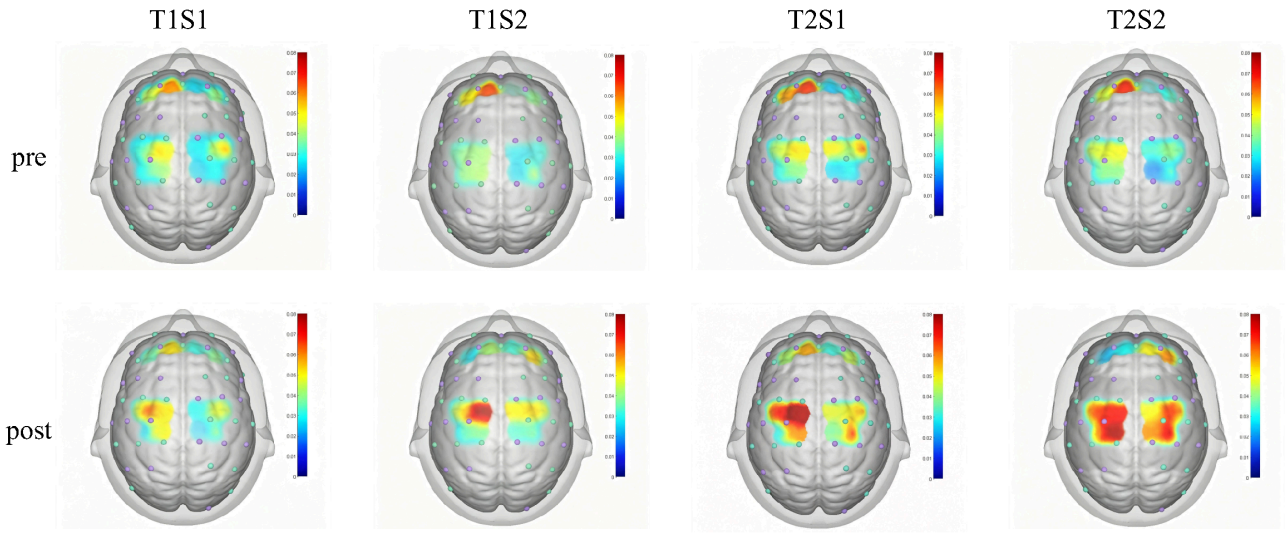


Figure 4

ΔHbO_2 in four intervention groups (top view)

The color bar represents the ΔHbO_2ranging from 0 to 0.08 mmol/L*mm. Higher HbO_2levels are indicated by colors closer to red, while lower levels are represented by colors closer to blue.

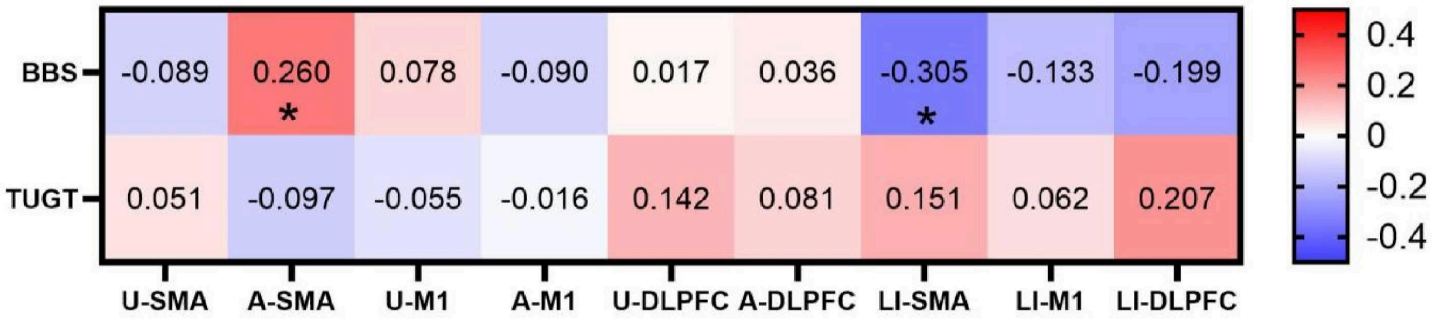


Figure 5

Spearman correlation analysis of function and cerebral cortex activation

* indicates that there is a statistical significance between the indicators, $p<0.05$.U-indicates the unaffected side; A-indicates the affected side; LI-indicates the partialization