

Mechanical Digitorum Sensory Stimulation Enhances Hemiplegic Upper Limb Motor Function in Stroke Patients by Increasing Cortical Excitability and Functional Connectivity

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Abstract

Background

Relieving flexor spasticity, enhancing extensor strength, and improving hand function in patients with stroke remain significant clinical challenges. Mechanical Digitorum Sensory Stimulation (MDSS), a novel therapy that applies precise mechanical pressure to the affected fingers, may address these issues; however, its effects and mechanisms have not been thoroughly studied.

Methods

Sixty convalescent patients with post-stroke hemiplegia were randomly assigned to a Control group (conventional rehabilitation + sham MDSS) or an MDSS group (conventional rehabilitation + MDSS) for 3–4 weeks. Muscle spasticity, strength, upper-limb motor function, and activities of daily living were assessed using the Modified Ashworth Scale (MAS), Manual Muscle Testing (MMT), Fugl-Meyer Assessment–Upper Extremity (FMA-UE), and Modified Barthel Index (MBI), respectively. Functional near-infrared spectroscopy (fNIRS) was used to measure oxyhemoglobin (HbO) concentrations in regions of interest (ROIs) during the resting state (RS) and task state (TS; i.e., MDSS) to evaluate cortical excitability and functional connectivity (FC) by calculating correlations of HbO concentration changes between specific ROIs.

Results

After the intervention, the MDSS group showed significantly lower MAS scores for all finger flexors ($P < 0.001$) and significantly higher MMT scores for all finger extensors, as well as higher FMA-UE and MBI scores ($P < 0.01$) compared with the Control group. Regarding cortical excitability, increases in HbO concentration were higher in most ROIs in the MDSS group than in the Control group, including 10 ROIs (83.33%) during RS and 11 ROIs (91.67%) during TS. Moreover, increases in FC across all ROI-to-ROI pairs were greater in the MDSS group than in the Control group during both RS and TS.

Conclusions

MDSS effectively alleviates flexor spasticity, enhances extensor strength, and improves upper-limb motor function in patients with stroke. These effects are associated with enhanced cortical excitability and strengthened functional connectivity, supporting MDSS as a promising rehabilitation strategy for hemiparetic hand recovery.

Trial registration

1. Background

Stroke is one of the leading causes of long-term disability in adults worldwide [1]. Hemiparetic motor deficits are a primary clinical manifestation in patients with stroke [2]. To date, more than half of stroke survivors continue to experience upper limb motor dysfunction months after stroke onset; in many cases, these impairments persist for life [3, 4].

Approximately one month after stroke, patients commonly develop finger flexor spasticity on the affected side, characterized by flexion deformities of the fingers, a semi-clenched fist posture, and an inability to actively extend the fingers, all of which severely compromise hand function [5, 6]. Moreover, conventional rehabilitation therapies are often ineffective at alleviating finger flexor spasticity or restoring active finger extension. As a result, hand dysfunction frequently becomes chronic or permanent, substantially diminishing patients' quality of life [7, 8].

Kattenstroth et al [9] demonstrated that the fingertips are more sensitive than other body regions owing to their dense distribution of nerve endings and tactile receptors. Electrical stimulation of the fingertips can selectively activate specific somatosensory cortical areas. Following central nervous system injury, appropriate sensory stimulation of the fingers can enhance cortical excitation and facilitate limb movement [10, 11]. Notably, Kattenstroth et al. [9] reported that two weeks of electrical stimulation applied to the fingertips of the hemiparetic hand in subacute stroke patients significantly improved upper-limb sensory and motor function.

To address the clinical challenge of rehabilitating hand function after stroke and building on the rich sensory innervation of the fingertips, our team developed a novel intervention for stroke rehabilitation: Mechanical Digitorum Sensory Stimulation (MDSS). Clinical observations and preliminary studies [12, 13] have shown that MDSS, which applies precise mechanical pressure to the fingernail beds of the hemiparetic hand, can rapidly and significantly reduce finger flexor spasticity and promote active finger extension in patients with stroke. Furthermore, our recent findings [14] indicate that a single MDSS session can significantly enhance brain function, as detected by functional magnetic resonance imaging (fMRI). However, the cumulative effects of repeated MDSS sessions on hemiparetic upper-limb motor function (including hand function) and the associated neural mechanisms remain unclear.

Functional near-infrared spectroscopy (fNIRS) is a novel, noninvasive neuroimaging technique that indirectly assesses brain function by measuring changes in oxyhemoglobin (HbO) concentration associated with neuronal activation [15]. Compared with fMRI, fNIRS is more convenient and safer, and it is particularly sensitive to cortical hemodynamic changes during sensory and motor tasks [16]. Consequently, fNIRS has been increasingly applied in neuroscience and neurorehabilitation research in recent years [17, 18].

Therefore, this single-blind randomized controlled trial aims to evaluate the effects of a course (3–4 weeks) of MDSS on upper limb motor function, including hand function, in patients with poststroke hemiparesis using standardized clinical assessments. In addition, fNIRS will be used to further elucidate the neural mechanisms underlying the therapeutic effects of MDSS, with the ultimate goal of providing a novel and effective intervention for upper-limb motor rehabilitation after stroke.

2. Methods

2.1 Study participants

This study was a single-center, single-blind, randomized controlled trial. The sample size was calculated using G*Power software (version 3.1.9.2; Franz Faul, University of Kiel, Germany). Based on previous literature [19] and assuming a significance level (α) of 0.05, statistical power ($1 - \beta$) of 0.90, and an effect size of 0.6, a minimum of 60 participants was required.

Between August 2022 and April 2023, stroke patients with hemiparesis who were hospitalized in the Department of Rehabilitation Medicine at our hospital were consecutively screened and recruited according to predefined inclusion and exclusion criteria. The study protocol was approved by the Ethics Committee of our hospital (Approval No.: YX2022-089) and registered in the Chinese Clinical Trial Registry (ChiCTR2200063792). The trial was conducted in accordance with the Declaration of Helsinki (2008 revision). All participants were fully informed of the study objectives and procedures and provided written informed consent before enrollment.

2.2 Inclusion, exclusion, and termination criteria

Inclusion criteria

Participants were eligible if they met all of the following criteria: (1) age 40–80 years; diagnosis of cerebral hemorrhage or cerebral infarction confirmed by cranial magnetic resonance imaging (MRI) or computed tomography (CT); disease duration of 1–6 months, and stable vital signs; (2) presence of finger flexor spasticity on the hemiparetic side [Modified Ashworth Scale (MAS) score ≥ 1]; (3) essentially normal cognitive function (Mini-Mental State Examination score ≥ 21) and ability to cooperate with the intervention and assessments; and (4) willingness to participate and provision of written informed consent.

Exclusion criteria

Participants were excluded if they met any of the following criteria: (1) history of two or more strokes; (2) progressive neurological deterioration, unstable vital signs, severe cardiac, hepatic, or renal dysfunction, or malignant tumors; (3) normal or decreased flexor muscle tone in the hemiparetic hand; (4) inability to cooperate with the intervention or assessments; (5) pregnancy or lactation; (6) acute infection accompanied by fever; (7) concurrent participation in another clinical trial; or (8) refusal to provide informed consent.

Termination Criteria

Participants were withdrawn from the study if any of the following occurred: (1) poor compliance with the intervention protocol; (2) voluntary withdrawal by the participant or the participant's family; or (3) clinical deterioration that made continued participation inappropriate.

2.3 Study procedures

2.3.1 Baseline data collection

Baseline demographic and clinical data were collected, including age, sex, disease duration, length of hospitalization, stroke type, affected side, and comorbidities (e.g., hypertension and diabetes mellitus).

2.3.2 Randomization and blinding

Participants were randomly assigned to either the MDSS group or the Control group using a random number table. Participants were blinded to group allocation. Except for personnel administering MDSS or sham-MDSS, all investigators—including conventional rehabilitation therapists, outcome assessors, and data analysts—were blinded to group assignments.

2.3.3 Digitorum sensory stimulator (DSS)

A Digitorum Sensory Stimulator (DSS; Hefei Bianri Medical Technology Co., Ltd., China) was developed to ensure precise delivery of MDSS. The device provides real-time feedback on stimulation intensity in Newtons (N). Detailed information on DSS structure and operation has been described previously [12, 13].

2.3.4 Rehabilitation interventions

Control group: Participants received conventional rehabilitation therapy combined with sham-MDSS. Conventional rehabilitation consisted of active movements of the unaffected limb; active, passive, or assisted movements of the affected limb; and neuromuscular electrical stimulation. Each session for all rehabilitation components lasted 20–40 min, once daily, 6 days per week, for 3–4 weeks.

For sham-MDSS, a pressure value (randomly displayed between 10 and 30 N) was shown on the DSS screen without applying actual pressure. The device was sequentially placed on the nail bed roots of the five fingers on the hemiparetic side (from the little finger to the thumb). Each finger received sham stimulation for 5 s, with 10-s intervals between fingers, resulting in a total session duration of approximately 65 s. Sham-MDSS was administered three times daily (morning, noon, and evening), 6 days per week, for 3–4 weeks.

MDSS group: In addition to the same conventional rehabilitation, participants received MDSS therapy. Patients were seated or placed in a supine position, and a trained researcher applied DSS sequentially to the nail bed roots of the five fingers on the hemiparetic side (from the little finger to the thumb). Stimulation intensity was set at a tolerable level that elicited active finger extension (typically 10–30 N).

Each finger was stimulated for 5 s, with 10-s intervals between fingers, for a total session duration of approximately 65 s. MDSS was administered three times daily (morning, noon, and evening) for 6 days per week for 3–4 weeks (Fig. 1).

2.4 Safety and acceptability assessment

Participants were monitored throughout the study for adverse events, including seizures, recurrent cerebral hemorrhage or infarction, pulmonary embolism, myocardial infarction, and death. After the first and final MDSS sessions, stimulation-related pain was assessed using the pain visual analog scale (pVAS) [20].

Treatment acceptability was evaluated after completion of the intervention using a four-item questionnaire: (Q1) “Is the MDSS therapy motivating?” (0 = no, 1 = yes); (Q2) “Would you recommend MDSS to other stroke patients?” (0 = no, 1 = yes); (Q3) “Has MDSS therapy led to noticeable improvements?” (0 = no, 1 = yes); and (Q4) “How comfortable was the MDSS therapy?” (0 = very uncomfortable, 10 = very comfortable) [21].

2.5 Efficacy evaluation

Evaluation timing: Clinical assessments and fNIRS examinations were conducted at baseline (within 2 days of enrollment) and at the end of the intervention (within 2 days before discharge).

Evaluators: All assessments were performed by trained evaluators who were blinded to group allocation.

2.5.1 Clinical outcome measures

2.5.1.1 Pain visual analog scale (pVAS)

The pVAS was used to assess pain intensity during MDSS. The scale consists of a 10-cm horizontal line scored from 0 (no pain) to 10 (severe, intolerable pain). Scores of 1–3 indicate mild pain, 4–6 indicate moderate pain, and 7–10 indicate severe pain [20].

2.5.1.2 Modified ashworth scale (MAS)

The MAS was used to assess spasticity of the flexor pollicis longus, flexor digitorum superficialis (III, i.e., the middle finger), and flexor digitorum superficialis (V, i.e., the little finger) on the hemiparetic side. Scores range from 0 (normal tone) to IV (rigidity). For quantitative analysis, grades 0, I, I+, II, III, and IV were converted to numerical scores of 0–5, respectively [22].

2.5.1.3 Manual muscle testing (MMT)

Muscle strength was assessed using the Medical Research Council (MRC) MMT scale. Strength was graded on a 13-point scale and converted to a 0–12 score, with higher scores indicating greater strength. Assessments included both flexor and extensor muscles of the hemiparetic hand [23].

2.5.1.4 Fugl–Meyer Assessment (FMA)

Motor function was evaluated using the Fugl–Meyer Assessment. Only the upper extremity subscale (FMA-UE; maximum score, 66) was administered, with higher scores indicating better motor performance [24, 25].

2.5.1.5 Modified Barthel Index (MBI)

Activities of daily living were assessed using the Modified Barthel Index (MBI; maximum score, 100). Higher scores reflect greater functional independence [26].

2.6 Assessment of cortical excitability and functional connectivity

2.6.1 fNIRS instrumentation

A multichannel fNIRS system (NirScan-6000C; Danyang Huichuang Medical Technology Co., Ltd., Jiangsu, China) was used. Data were acquired at a sampling frequency of 11 Hz using three wavelengths (730, 808, and 850 nm) to quantify changes in oxyhemoglobin (HbO) concentration.

Based on the international 10–20 system, 16 light sources and 16 detectors (source–detector distance, 3 cm) were positioned bilaterally over predefined regions of interest (ROIs), including the prefrontal cortex (PFC), premotor and supplementary motor cortex (PMC), primary motor cortex (M1), primary somatosensory cortex (S1), supramarginal gyrus (SMG), and occipital lobe (OL), yielding a total of 34 channels [27]. For each hemisphere, channel distribution included 7 channels over the PFC, 3 over the PMC, 2 over M1, 2 over S1, 2 over SMG, and 1 over the OL [14] (Fig. 2).

2.6.2 fNIRS data acquisition

All fNIRS assessments were conducted in a quiet, controlled environment by trained researchers.

Preparation phase:

Participants were instructed to obtain sufficient sleep and to refrain from smoking and caffeine intake before testing. Participants were familiarized with the experimental procedures and trained to comply with task requirements.

First, stimulation pressure levels corresponding to pVAS scores of 3 and 4 were determined for each participant. Using the DSS, pressure was applied to the nail bed root of the little finger on the hemiparetic side, and participants rated pain intensity using the pVAS. The pressure values that elicited pVAS scores of 3 and 4 were recorded for subsequent task calibration.

Second, resting-state (RS) training was conducted. Participants were instructed to sit quietly without intentional thoughts or movements. Each training cycle consisted of 15 s of RS, followed by 10 s of

MDSS (stimulation pressure corresponding to pVAS = 4), and then 3 min of RS. Three cycles were completed per session. After each session, participants rated their ability to maintain RS using a task visual analog scale (tVAS; 100-mm line), with higher scores indicating better performance. A minimum tVAS score of 80 mm was required. Participants who failed to meet this criterion after three training sessions were excluded.

Subsequently, participants were seated comfortably, the fNIRS cap was fitted, and hair beneath the optodes was adjusted to ensure optimal signal quality. Participants rested with both hands placed naturally on the thighs for 5 min before data acquisition.

Formal data acquisition:

The fNIRS assessment consisted of block-task and continuous-task paradigms (Fig. 3). For block-task acquisition, MDSS was applied to the affected hand. Each block comprised 10 s of MDSS task state (TS) followed by 15 s of RS, and five blocks were completed. After a 5-min rest period, continuous-task acquisition was performed, consisting of 3 min of RS followed by 3 min of MDSS task state. Upon completion, participants completed the tVAS again to assess RS compliance during data acquisition. Data from participants with tVAS scores < 80 mm were excluded from further analysis.

During all MDSS task states, stimulation was delivered to the nail bed root of the little finger on the hemiparetic side using the DSS. Stimulation intensities corresponded to pVAS = 4 during block tasks and pVAS = 3 during continuous tasks.

2.6.3 fNIRS data processing

Due to variability in lesion laterality among participants, data from individuals with right-hemispheric lesions were spatially mirrored to standardize lesion orientation for group-level analyses [27]. After mirroring, the left hemisphere consistently represented the lesioned side, while the right hemisphere represented the non-lesioned side.

Data preprocessing was conducted using NirSpark software (Danyang Huichuang Medical Equipment Co., Ltd., Jiangsu, China). Segments deemed invalid or exhibiting excessive noise were excluded. Motion artifacts were identified and corrected using spline interpolation (standard deviation threshold: 6; peak threshold: 0.5). A Butterworth band-pass filter (0.01–0.10 Hz) was applied to attenuate physiological and system-related noise. Optical density signals were subsequently converted into changes in HbO concentration using the modified Beer–Lambert law, with a differential pathlength factor of 6 [28].

2.6.4 fNIRS data analysis

2.6.4.1 Block-task analysis

Block-task data were analyzed using the BlockAverage module in NirSpark. The mean HbO concentration during the 2 s preceding task onset served as the baseline. HbO signals from 0 to 10 s after task onset

were defined as the TS, and signals from 11 to 25 s were defined as the RS.

Baseline values were subtracted from the TS and RS signals to obtain $\Delta\text{HbO_TS}$ and $\Delta\text{HbO_RS}$, respectively. Values from the five task blocks were averaged to compute mean TS and RS ΔHbO for each channel. Channel-level ΔHbO values within each ROI were then averaged to derive ROI-level ΔHbO values, which were used as indices of cortical excitability during task and resting states. Higher ΔHbO values reflected greater cortical excitability [29, 30].

2.6.4.2 Continuous-task analysis

Cortical functional connectivity (FC) was analyzed using the Network module in NirSpark. HbO time series were extracted for each channel during the 3-min RS and the 3-min MDSS TS. Pearson correlation coefficients (r) were calculated for all channel pairs, with each coefficient representing FC strength [31].

For ROI-level analysis, FC between two ROIs was calculated as the mean of all pairwise channel correlations between the two ROIs [30]. Higher r values indicated stronger functional connectivity. For intergroup comparisons, correlation coefficients were normalized using Fisher's r -to- z transformation, and multiple comparisons were corrected using the false discovery rate (FDR) method [32].

2.7 Statistical analysis

Data organization and statistical analyses were independently performed by two researchers blinded to group allocation, under the supervision of professional statisticians. Statistical analyses were performed using NirSpark software and SPSS version 25.0 (IBM Corp., Armonk, NY, USA). Figures were generated using NirSpark.

The normality of continuous variables was assessed using the Shapiro–Wilk test, and all variables were found to be normally distributed. Continuous data are reported as mean $\pm$ standard deviation (SD). Between-group comparisons were conducted using independent-samples t -tests, and within-group comparisons were conducted using paired-samples t -tests.

Ordinal data are presented as medians with interquartile ranges [M (P25, P75)]. Within-group comparisons were conducted using the Wilcoxon signed-rank test, and between-group comparisons using the Mann–Whitney U test. Categorical variables are presented as counts and compared using the chi-square (χ^2) test.

All statistical tests were two-tailed, and a P value < 0.05 was considered statistically significant.

3. Results

3.1 Security and acceptability

A total of 68 stroke patients met the eligibility criteria and provided informed consent. Of these, 35 participants were randomly assigned to the Control group and 33 to the MDSS group. Seven participants (five in the Control group and two in the MDSS group) discontinued the intervention due to early hospital discharge and subsequently withdrew from the study. All participants in the MDSS group completed the resting-state training. However, one participant in the MDSS group was excluded from the fNIRS analysis because the task visual analog scale (tVAS) score was below 80 mm after formal fNIRS data acquisition prior to the intervention. As a result, data from 60 participants (30 per group) were included in the final analysis.

No adverse events related to the intervention were observed during the study period.

In the MDSS group, the pVAS scores at the first and final stimulation sessions were 4 (4, 5) and 3 (3, 4), respectively. Throughout the study, pVAS scores ranged from 2 to 6, indicating that MDSS induced only mild to moderate pain. The stimulation pressures corresponding to pVAS scores of 3 and 4 were 20.74 ± 3.58 N and 23.17 ± 3.97 N, respectively. No stimulation-related injuries were reported.

Among the 30 participants in the MDSS group who completed the acceptability questionnaire, 96.67% reported that the therapy was motivating (Q1), 93.33% indicated they would recommend MDSS to other stroke patients (Q2), and 90.00% perceived tangible improvements following the intervention (Q3). The overall comfort level of MDSS was rated at 6.23 ± 1.38 out of 10 (Q4).

3.2 Baseline characteristics

Baseline characteristics were comparable between the Control and MDSS groups. No statistically significant differences were found in sex, age, disease duration, length of hospitalization, stroke type (cerebral hemorrhage or infarction), affected side (left or right hemiplegia), or the presence of hypertension or diabetes (all $P > 0.05$). Detailed baseline data are presented in Supplemental Table 1.

3.3 Clinical scale outcomes

3.3.1 Modified Ashworth scale (MAS)

Prior to the intervention, MAS scores for the three finger flexors [flexor pollicis longus, flexor digitorum superficialis (☒), and flexor digitorum superficialis (☒)] did not differ significantly between groups ($P > 0.05$). Following the intervention, MAS scores for all three muscles were significantly lower in the MDSS group than in the Control group (all $P < 0.001$).

Within-group comparisons revealed that, in the Control group, only the flexor digitorum superficialis (☒) showed a significant reduction in MAS score after the intervention ($P < 0.05$). In contrast, the MDSS group exhibited significant reductions in MAS scores for all three finger flexors (all $P < 0.001$). Detailed results are provided in Supplemental Table 2.

3.3.2 Manual muscle testing (MMT)

In the Control group, only the MMT score of the flexor digitorum (FD) showed a significant improvement after the intervention compared with baseline ($P < 0.05$). In the MDSS group, significant post-intervention improvements were observed in the flexor digitorum (FD) ($P < 0.05$), flexor pollicis, extensor pollicis, extensor digitorum (ED), and extensor digitorum (ED) ($P < 0.01$).

No significant between-group differences in MMT scores were observed at baseline ($P > 0.05$). After the intervention, the MDSS group demonstrated significantly higher MMT scores for the flexor pollicis ($P < 0.05$) and all three extensor muscles [extensor pollicis, extensor digitorum (ED), and extensor digitorum (ED); all $P < 0.01$] compared with the Control group. Results are summarized in Supplemental Table 3.

3.3.3 FMA-UE and MBI scores

Both groups showed significant improvements in FMA-UE and MBI scores following the intervention compared with baseline (all $P < 0.001$). No significant differences were found between the groups at baseline ($P > 0.05$). After the intervention, the MDSS group exhibited significantly higher FMA-UE and MBI scores than the Control group (both $P < 0.01$). Detailed data are provided in Supplemental Table 4.

3.4 fNIRS results

3.4.1 Oxyhemoglobin (HbO) concentrations

Within-group comparisons:

In the Control group, HbO concentrations in most ROIs were higher after the intervention than before, during both the RS and the TS, except for LS1 during RS and LOL during TS, where HbO levels were higher prior to the intervention. However, none of these changes reached statistical significance (all $P > 0.05$).

In the MDSS group, during RS, HbO concentrations increased after the intervention in all ROIs except LOL, with significant increases observed in RPFC, LPFC, and LPMC ($P < 0.05$). During TS, HbO concentrations in all ROIs were significantly higher after the intervention than at baseline (all $P < 0.05$). These findings are presented in Supplemental Tables 5 and 6 and illustrated in Figs. 4 and 5.

Between-group comparisons of HbO changes:

Except for ROL and LOL during RS, and ROL during TS—where the Control group showed greater pre-post differences, the MDSS group exhibited larger changes in HbO concentrations across all other ROIs during both RS and TS. However, none of these between-group differences reached statistical significance (all $P > 0.05$). Results are shown in Supplemental Table 7 and Fig. 6.

3.4.2 Cortical functional connectivity

Within-group comparisons:

In the Control group, during RS, 44 (66.67%) ROI–ROI functional connections were stronger before the intervention, while 22 (33.33%) were stronger afterward. During TS, 34 (51.52%) connections were stronger before the intervention, and 32 (48.48%) were stronger afterward. No significant differences were detected in any ROI–ROI functional connections between pre- and post-intervention states during either RS or TS (all $P > 0.05$).

In contrast, the MDSS group demonstrated consistent increases in functional connectivity following the intervention during both RS and TS. Specifically, 53 ROI–ROI connections (80.30%) during RS and 37 connections (56.06%) during TS showed significant post-intervention enhancement compared with baseline (all $P < 0.05$). These results are detailed in Supplemental Tables 8 and 9 and illustrated in Fig. 7.

Between-group comparisons:

For both RS and TS, the MDSS group exhibited greater pre–post intervention changes in functional connectivity than the Control group. Notably, 32 connections (48.48%) during RS and 5 connections (7.58%) during TS demonstrated significantly greater increases in the MDSS group compared with the Control group ($P < 0.05$). These findings are presented in Supplemental Table 10 and illustrated in Fig. 8.

4. Discussion

Recovery of clinical function after stroke fundamentally depends on the restoration of brain function, a process underpinned by neuroplasticity, the brain's capacity to compensate for damaged regions through functional reorganization. In this study, fNIRS was used to characterize changes in cortical activation patterns and functional network connectivity during hand task execution before and after the MDSS intervention. From the perspective of cortical remodeling, the findings provide mechanistic insight into how MDSS facilitates upper limb motor recovery in stroke patients and highlight its potential as an innovative rehabilitation strategy in clinical practice.

This single-blind randomized controlled trial demonstrated significant improvements in upper-limb motor function in both the Control and MDSS groups following the intervention. As shown in Supplemental Table 4, FMA-UE and MBI scores were significantly higher post-treatment compared with baseline in both groups ($P < 0.01$), indicating that both conventional rehabilitation alone and conventional rehabilitation combined with MDSS effectively improved upper limb motor function and activities of daily living over a 3–4-week intervention period. These findings are consistent with previous reports by Yao et al [13].

Importantly, the results demonstrate that MDSS accelerates the reduction of finger flexor spasticity, enhances extensor muscle strength, and promotes upper limb motor recovery in stroke patients. After one treatment course, MAS scores for the flexor pollicis longus, flexor digitorum superficialis (☒), and flexor digitorum superficialis (☒) were significantly lower in the MDSS group compared with the Control group (all $P < 0.001$; Supplemental Table 2). Conversely, MMT scores for the extensor pollicis, extensor digitorum (☒), and extensor digitorum (☒) were significantly higher in the MDSS group following the

intervention (all $P < 0.01$; Supplemental Table 3). These findings indicate that MDSS effectively reduces pathological finger flexor hypertonia while concurrently enhancing extensor muscle strength, both of which are essential for the functional recovery of the hemiplegic hand.

Consistent with these neuromuscular improvements, the MDSS group exhibited significantly greater post-intervention increases in FMA-UE and MBI scores compared with the Control group (all $P < 0.01$; Supplemental Table 4). This suggests that the addition of MDSS to conventional rehabilitation confers additive benefits for upper-limb motor recovery and activities of daily living, consistent with previous observations by Yao et al [13].

Beyond behavioral outcomes, a single MDSS course was found to broadly enhance cortical excitability in patients with post-stroke hemiplegia. Increases in task- and resting-state oxyhemoglobin (HbO) concentrations measured by fNIRS are widely regarded as indicators of enhanced cortical activation and neurovascular coupling, both of which are critical substrates for functional recovery following ischemic brain injury [17]. As shown in Supplemental Tables 5 and 6, HbO concentrations in all ROIs in the Control group did not increase significantly after the intervention during either the resting or task state. In contrast, the MDSS group exhibited significant post-intervention increases in HbO in 3 ROIs (25%) during the resting state and in all ROIs (100%) during the task state (all $P < 0.05$). Moreover, the magnitude of HbO increases was greater in the MDSS group than in the Control group across most ROIs (Supplemental Table 7), indicating that 3–4 weeks of MDSS generally enhanced cortical excitability in stroke patients.

These findings are supported by Yao et al. [14], who reported that a single MDSS session applied to the five fingers of the affected hand significantly enhanced resting-state fMRI signals across multiple ROIs in stroke patients. Although the MDSS group in the present study exhibited greater overall increases in HbO than the Control group, between-group differences in individual ROIs did not reach statistical significance, which may be attributed to the relatively short intervention duration.

In addition to enhancing cortical excitability, MDSS also markedly improved FC. In the Control group, only a limited proportion of ROI–ROI connections increased following the intervention during both resting and task states, and none of these changes reached statistical significance (Supplemental Table 8). In contrast, all ROI–ROI FCs increased in the MDSS group across both states, with a substantial proportion showing significant enhancement relative to baseline (Supplemental Table 9). Furthermore, increases in FC were consistently greater in the MDSS group than in the Control group during both resting and task states, with several connections demonstrating statistically significant between-group differences (Supplemental Table 10).

Restoration of brain function, including cortical excitability and functional connectivity, is a prerequisite for clinical recovery after stroke. In addition to focal structural damage, stroke induces widespread network-level dysfunction that affects both adjacent and remote brain regions [33]. In neuroimaging studies, cortical excitability reflects neuronal responsiveness to external stimuli, whereas functional connectivity represents the temporal synchronization of activity between brain regions [34, 35].

Converging evidence from fMRI and fNIRS studies indicates that restoration of interhemispheric and intra-network connectivity within sensorimotor circuits is a key neural marker of favorable motor recovery, whereas persistent network disruption is associated with poorer functional outcomes [36, 37].

Previous neuroimaging studies have consistently demonstrated reduced cortical excitability [35, 38] and weakened interregional functional connectivity [39–41] in stroke patients compared with healthy controls. Interventions such as transcranial direct-current stimulation have been shown to enhance cortical activation and functional connectivity, accompanied by corresponding functional improvements [35, 41]. Taken together, the present findings suggest that MDSS broadly enhances cortical excitability and network integration in stroke patients. These neurophysiological changes may facilitate upper-limb motor recovery by improving the brain's ability to perceive, process, and respond to external sensory input, thereby providing a plausible neurobiological mechanism for the therapeutic effects of MDSS.

5. Conclusions

In summary, the MDSS technology developed by our research group effectively reduces flexor muscle spasticity, enhances extensor muscle strength, and improves upper limb motor function and activities of daily living in patients during the post-stroke recovery phase. These therapeutic effects are likely mediated by enhanced cortical excitability and strengthened functional connectivity between brain regions. Due to its simplicity, safety, and lack of apparent side effects, MDSS demonstrates high levels of patient acceptance and satisfaction. Collectively, these findings suggest that MDSS is a promising, clinically feasible therapeutic approach for improving upper-limb motor function after stroke.

Limitations and Future Work

This study has several limitations. First, therapeutic effects were evaluated primarily in terms of motor function, without consideration of cognitive, psychological, or speech-related outcomes. Second, although MDSS was associated with greater enhancement of cortical excitability compared with conventional rehabilitation alone, between-group differences did not reach statistical significance, possibly due to the relatively short intervention and observation period of 3–4 weeks.

Third, the current DSS device requires manual operation and delivers sequential stimulation to each finger, with relatively short stimulation durations, which may limit its clinical applicability and therapeutic efficiency.

Future studies should extend the intervention duration, incorporate broader functional and neuropsychological assessments, and optimize the DSS device to enable more efficient and sustained stimulation. These improvements will support a more comprehensive evaluation of MDSS and further elucidate its role in post-stroke rehabilitation.

List of abbreviations

Mechanical Digitum Sensory Stimulation (MDSS)

the Modified Ashworth Scale (MAS)

Manual Muscle Testing (MMT)

Fugl–Meyer Assessment (FMA)

Fugl-Meyer Assessment–Upper Extremity (FMA-UE)

Modified Barthel Index (MBI)

Functional near-infrared spectroscopy (fNIRS)

oxyhemoglobin (HbO)

regions of interest (ROIs)

resting state (RS)

task state (TS)

functional connectivity (FC)

magnetic resonance imaging (MRI)

functional magnetic resonance imaging (fMRI)

computed tomography (CT)

Digitum Sensory Stimulator (DSS)

Newtons (N)

pain visual analog scale (pVAS)

the Medical Research Council (MRC)

prefrontal cortex (PFC),

premotor and supplementary motor cortex (PMC)

primary motor cortex (M1)

primary somatosensory cortex (S1)

supramarginal gyrus (SMG)

occipital lobe (OL)

task visual analog scale (tVAS)

false discovery rate (FDR)

standard deviation (SD)

Declarations

Ethics approval and consent to participate

This study was approved by the Medical Ethics Committee of the Second Hospital of Anhui Medical University [Approval No. YX2022-089] and performed in accordance with the Declaration of Helsinki. Informed consent to participate was obtained from all subjects involved in the study.

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

Conceptualization, W.H., Y.H.; methodology, W.H., H.Z.; software, H.Z.; validation, J.Y. and Y.Y.; formal analysis, Q.L., S.Z. and Y.Y.; investigation, W.H., J.Y.; resources, Y.H.; data curation, Y.M., Y.Y.; writing—original draft preparation, W.H., H.Z.; writing—review and editing, Q.L., Y.H.; visualization, W.H., Y.H.; supervision, R.W.; project administration, Y.H.; funding acquisition, Y.H.. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

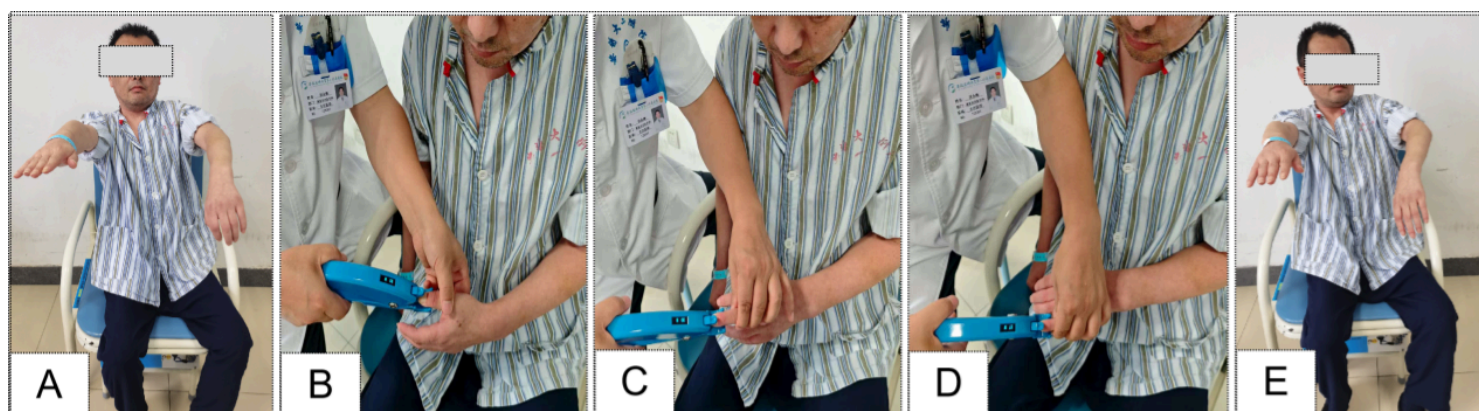


Figure 1

Implementation of MDSS

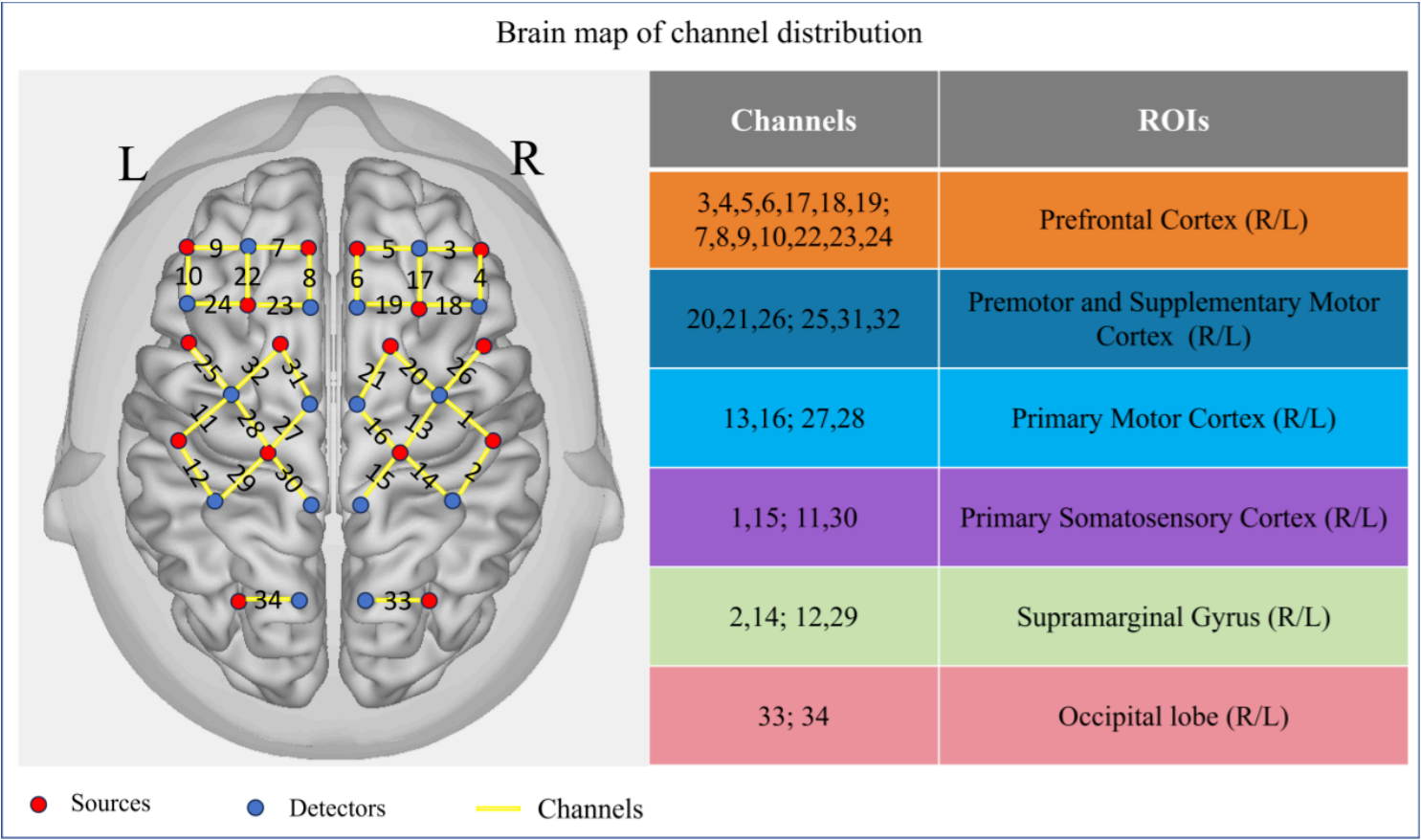


Figure 2

Arrangement of fNIRS sources and detectors

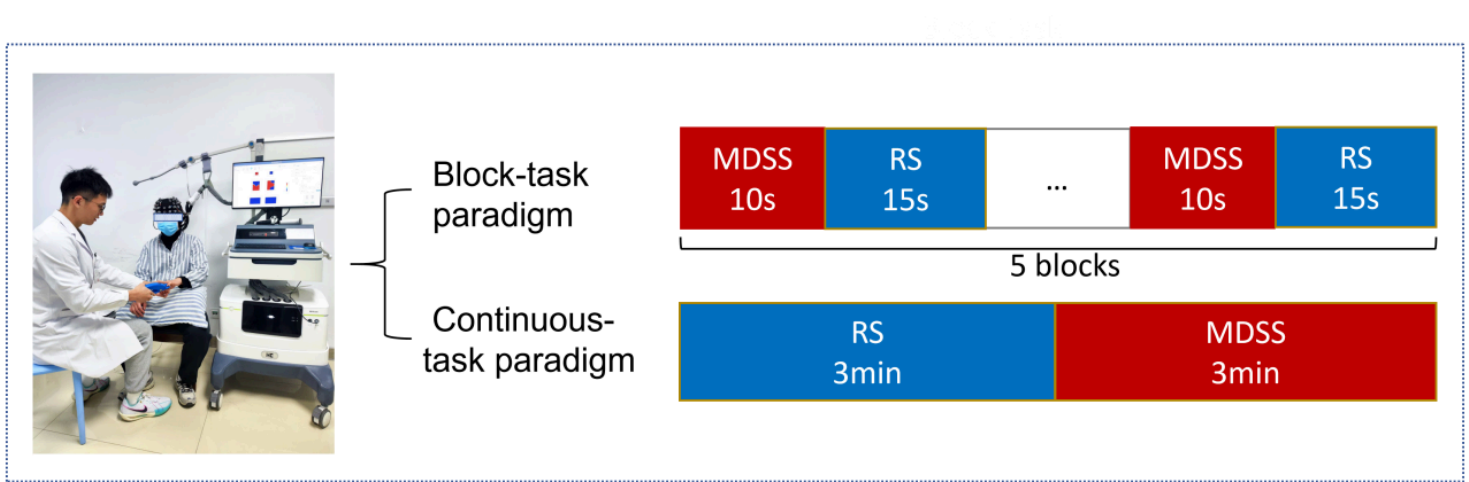


Figure 3

fNIRS collection in a patient with left hemiplegia (Left) and the flow chart of fNIRS data detection (Right)

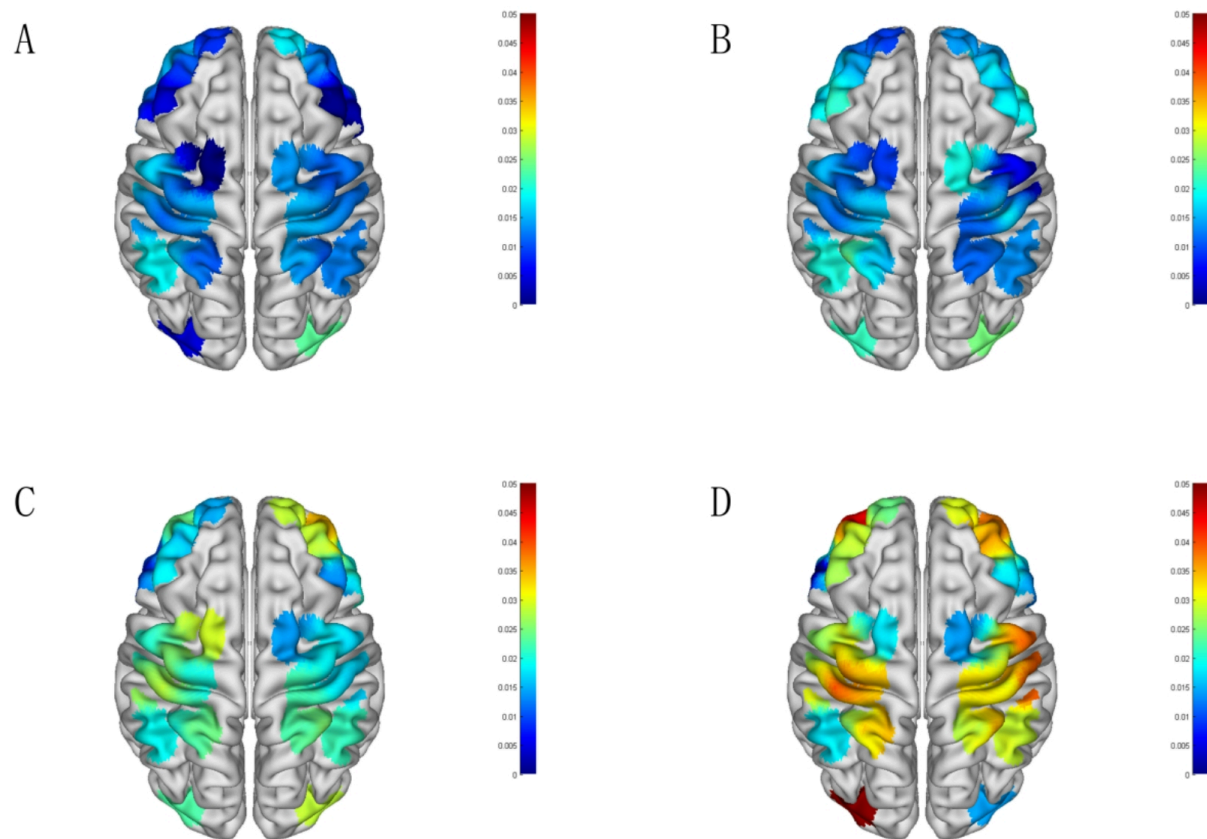


Figure 4

Cortical HbO concentration maps of each ROI in the Control group before and after the intervention

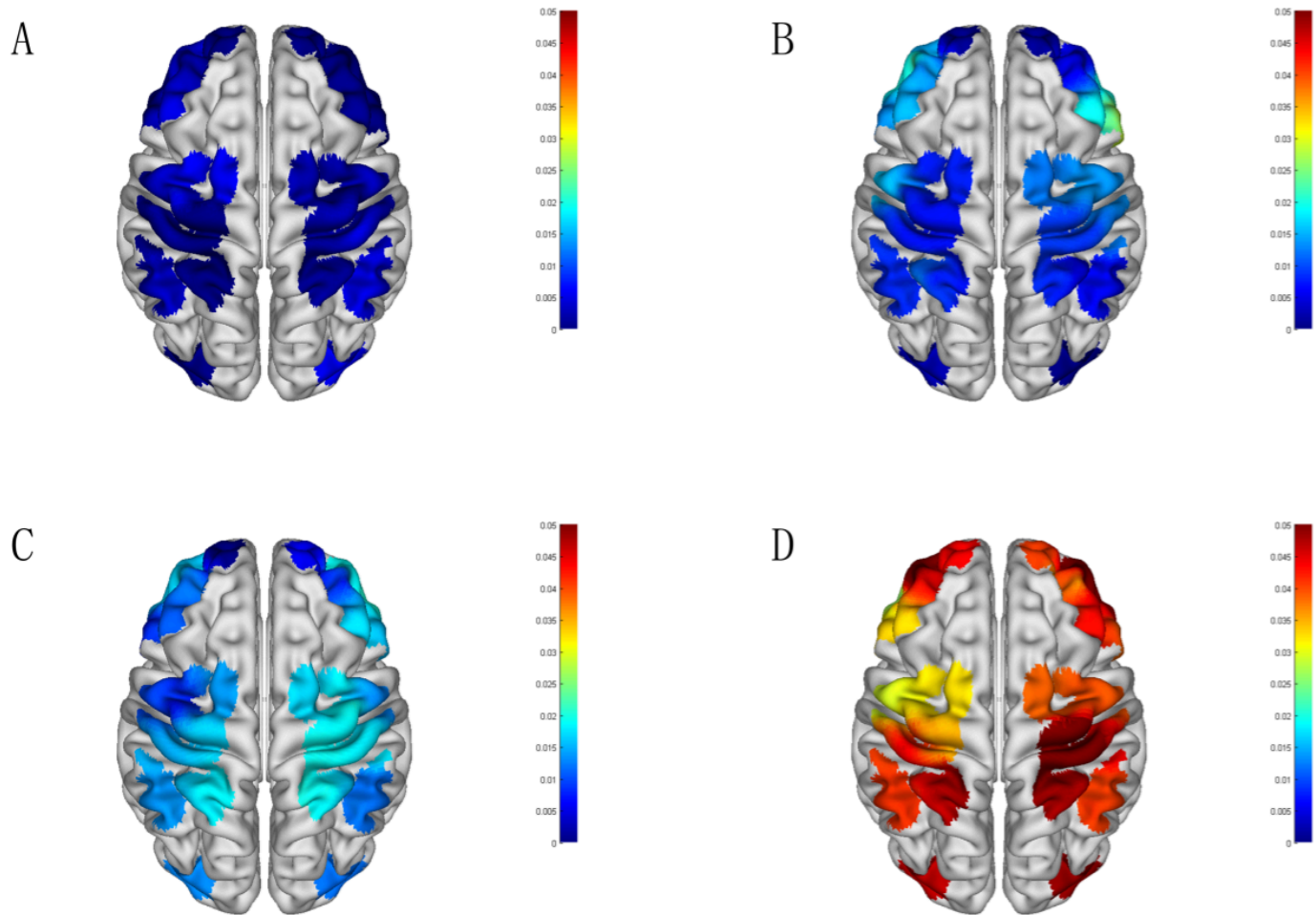


Figure 5

Cortical HbO concentration maps of each ROI in the MDSS group before and after the intervention

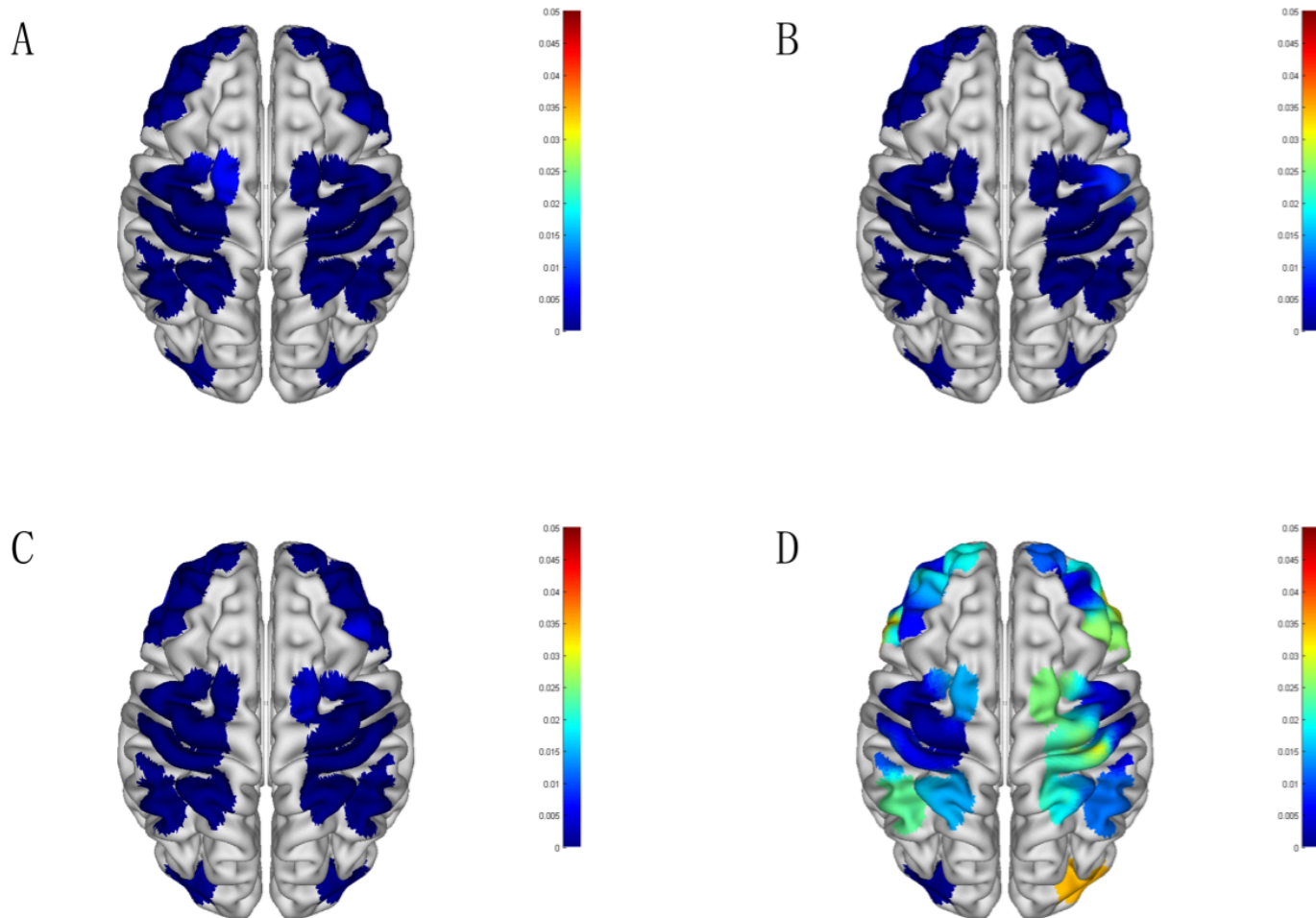


Figure 6

Cortical HbO concentration maps showing differences in HbO levels between the MDSS group and the Control group across ROIs

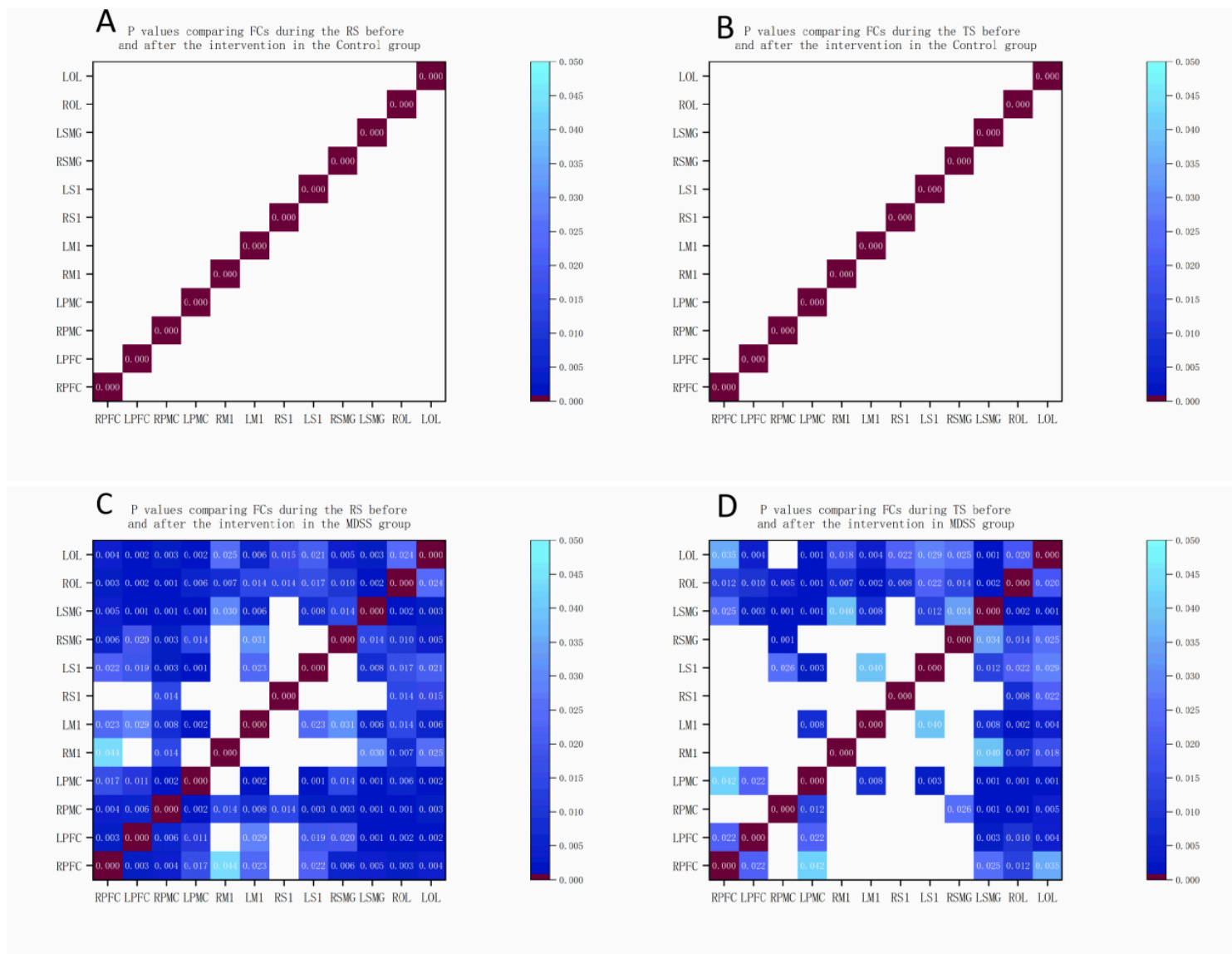


Figure 7

Heatmaps of P values comparing FC before and after the intervention in the Control and MDSS groups

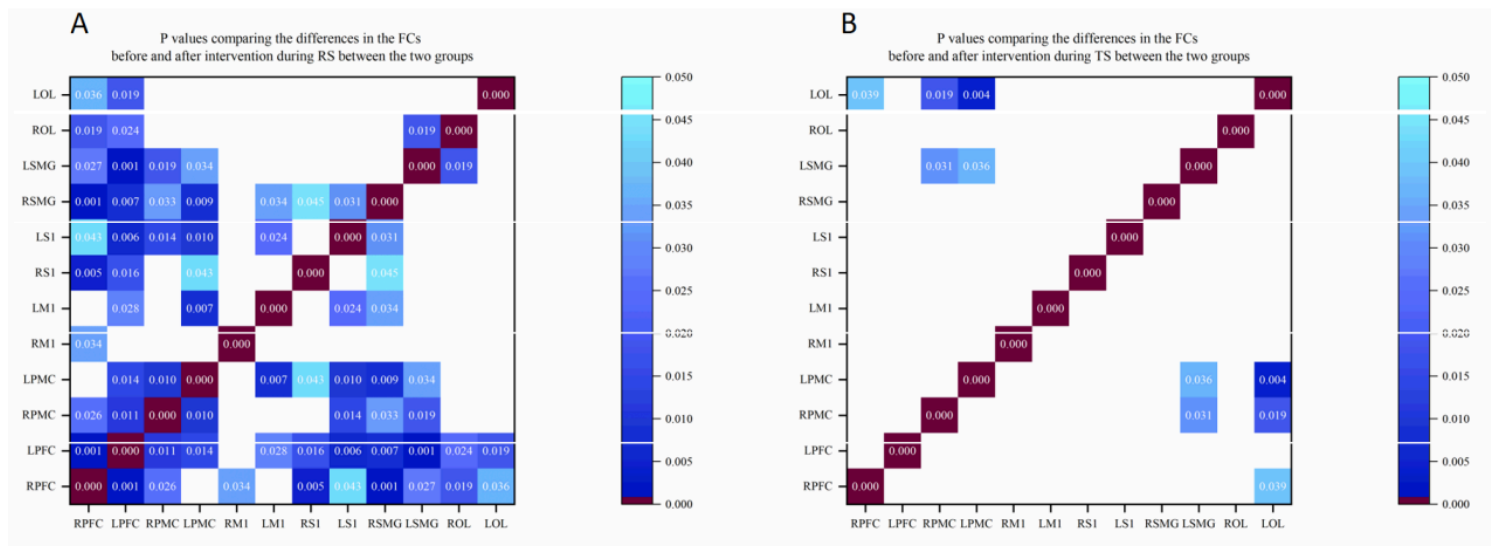


Figure 8

Heatmaps of P values comparing differences in FC before and after the intervention between the Control and MDSS groups

Supplementary Files

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

- [A video of a patient with hemiplegia before and after MDSS treatment.mp4](#)
- [CONSORT 2025 editable checklist.docx](#)
- [Graphical Abstract.png](#)
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