Effects of Brain Computer Interface-Robot System on upper limb function recovery in stroke patients: A Protocol Study for a Randomized Controlled Trial

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Method Article

Keywords: Brain Computer Interface, Upper Extremity, Neurofeedback, Stroke Rehabilitation, Hemiplegia
Abstract

Background /Objective

We developed a Brain Computer Interface (BCI) robot system for movement recovery of upper limb motor function in post-stroke patients with severe hemiplegia. We designed and performed a randomized controlled clinical trial (RCT) to explore our hypothesis that motor functional recovery using this BCI robot system could be improved in a greater level in severe hemiparesis compared to that of hand robot rehabilitation. And we also focus on the neuroplastic changes between the primary motor cortices (M1) and frontal cortices before and after BCI intervention.

Methods

We will conduct a single blind, parallel-group trial and recruit subacute or chronic poststroke patients with severe hemiparesis more than 90 days after onset (N=50). Participants are randomly allocated to 2 intervention groups (1:1) by a computer-generated assignment: the BCI-assisted hand robot training (the BCI group, BG, n=25) and a hand robot training not supported by BCI (the robot group, RG, n=25). Both interventions will be delivered 5 sessions per-week for totally 4 weeks as add-on therapies to conventional rehabilitation. Motor functions of the paretic hands will be measured at 4 points: pre- (baseline), mid- (after 10 sessions), post- (after 20 sessions) and one month follow-up (4 weeks after the intervention). All investigators assessing outcomes will be masked to treatment assignment. Improvement in Wolf Motor Function Test (WMFT) will be used as the primary outcome, while Fugl-Meyer Assessment (FMA), its wrist and hand (FMA-WH) sub-score and its shoulder and elbow (FMA-SE) sub-score will be served as secondary outcome measures. Neuroplastic changes will be measured by functional near-infrared spectroscopy (fNIRS) at baseline and one-month follow up after 20 sessions BCI training. Pearson correlation analysis is used to evaluate functional connectivity (FC) across time points.

Discussion

We expect the BCI-based rewarding of hand robot practice to promote the motor recovery in upper limb motor outcome and also, this clinical improvement to be sustained by a long-lasting neuroplasticity changes promote by the BCI-based intervention. Recruitment started in June 2021. This trial is currently in the data correcting phase. This RCT is expected to be completed by June 30, 2023.


Introduction

Annually, about 15 million people experience a stroke worldwide and about two thirds of stroke survivors have motor deficits associated with poor prognosis, especially the upper limb and hand motor dysfunction which seriously diminished the quality of life[1]. There are various rehabilitation techniques applied to motor function rehabilitation, but the serious and long-lasting motor function damage caused by stroke is so challenging. Traditional treatments such as physiotherapy and/or occupational therapy has provided limited recovery of motor function, resulting in the eventual disablity of the affected limb[2].
Researches has to be done to develop alternative approaches in terms of upper limb motor function recovery post-stroke. A few of innovative therapeutic strategies, such as constraint-induced movement therapy[3], motor imagery[4] repetitive transcranial magnetic stimulation[5], robot-assisted training[6], recommended for consideration in patients with moderate to severe hemiparesis according to the AHA/ASA guideline [7]. A systematic review found that robotic therapy improves arm function[8]. However, in a recent multi-center parallel-group randomised trial the absolute difference between effects of robotic and conventional therapy was small and of weak significance, which left the clinical relevance in question[9]. Recently, rehabilitative Brain Computer Interface (BCI) -robotic system which is based on motor imagery has emerged as promising techniques for stroke rehabilitation.

BCI-robot system is a communication pathway between human brain and robots, which performs as an external device and maximize brain activation during the process of training, by recording and decoding neural signals through MI and translating them into digital signals that can control assistive robots. This innovation of rehabilitative technology integrated motor imagery with robotic system. A systematic review found that MI can trigger neuroplasticity in ipsilesional motor cortex[10]. Several studies proved that BCI technology might induce the sensorimotor cortex excitability in healthy subjects and stroke patients. The change of the sensorimotor rhythm (SMR, 8–13 Hz) in electroencephalograms (EEGs) over the affected primary sensorimotor cortex is induced by MI of paretic finger extension or flexion, and transferred into control signals of external devices, including hand-orthoses, robots, or functional electric stimulation[11]. Real movement of the paretic arm or hand occurs with the help of the external devices. The amplitude of SMR decreases because of desynchronization of oscillatory-coupled neural membrane potentials, called event-related desynchronization (ERD) during the motor imaginary or the attempting of movement of the paretic finger. Therefore, EEG-ERD associated with an attempt of volitional movement of the paretic finger implies the recruitment of the remaining sensorimotor cortical neurons, which stands for the neuroplasticity during the process of the functional motor recovery.

Numerous clinical studies investigated the feasibility and efficacy of BCI-robotic system as an emerging motor rehabilitation technique in poststroke hemiplegia by assessing various neurophysiological and behavioral outcome measures. Zhao et al reported that finger motor function of subacute, severe hemiparetic patients improved after 4-week sessions of motor exercise with a BCI-controlled robot system relative to the Non-BCI group for 1 hour per day[12]. Moreover, they found the motor-evoked potential (MEP) and serum brain-derived neurotrophic factor (BDNF) levels enhanced in BCI controlled group, which are known as agents of increased neural activation of the central nervous system[12]. Meanwhile, evidences showed that in chronic stroke patients with minimal residual hand movements, BCI-driven robotic devices fixed to the paretic upper limb can be controlled through the regulation of motor-related oscillatory brain activity[13–15]. Besides, increasing studies demonstrated that improvement in the Fugl-Meyer assessment upper extremity motor function (FMA-UE) score was larger than minimum clinically important differences (MCID) of FMA-UE (4.25)[16] after BCI rehabilitation. While in a recent clinical study of patients with severe hemiparesis in chronic stroke, improvement in FMA-UE was only an average of 3.4 points after BCI-driven training[9]. These studies has shown large variability of changes founded in neuroplasticity and recovery outcomes associated with BCI approaches. Therefore, it is crucial that
further investigation of whether BCI-robotic therapy is more effective than dose-matched robotic system should be performed.

Functional magnetic resonance imaging (fMRI) revealed cortical activity of ipsilesional sensorimotor cortex was enhanced during execution of paretic finger movement after BCI training, while that of contralesional sensorimotor cortex was reduced[17]. It is known that afferent and proprioceptive feedback to the somatosensory cortex provided by the movements of assistive robotic devices could contribute to functional recovery. Functional connectivity (FC) studies poststroke also demonstrated that movements of the paretic limb were characteristic of abnormal inhibitory influence between contralesional and ipsilesional primary motor cortex (M1). And the degree of motor impairment was associated with the level of interhemispheric inhibition (IHI)[18]. Caria et al. revealed contralesional M1 negatively correlated with ipsilesional sensorimotor regions before BCI training [19]. BCI training reinforced ipsilesional brain activity and enhanced proprioceptive function of the affected hand, which elicited reorganization of somatosensory and motor-assemblies in severe chronic stroke. These results suggested that neuroplastic changes in central nervous system may play an essential role in the process of BCI-triggered functional recovery.

Recently, Functional Near-infrared Spectroscopy (fNIRS) as an emerging technology has gradually become a well-established neuroimaging tool in measuring the concentration change in oxy-Hb and deoxy-Hb which causes by brain activity. Cerebral oxygenation fluctuation signals can be recorded by fNIRS and be calculated the coherence and phase locking value (PLV), by which the FC of the brain networks could be assessed[20]. Compared with fMRI, fNIRS measurement has larger advantages in upright position with a higher temporal resolution (~ 10 Hz) and in task state without physical restraint. Several previous studies using fNIRS have successfully observed FC during both the rest and the task state in healthy volunteers and stroke patients[21].

Our hypothesis is that motor recovery of upper extremity in severe hemiparesis using BCI robotic system could have a stronger improvement compared to that of hand robot rehabilitation. We designed a single blind, randomized parallel-group trial and planned to perform analysis of (1) changes in FC between brain regions involved the primary motor cortices and frontal cortices and (2) changes in behavioral outcome measures related to motor function after BCI intervention. Results are subsequently used to identify correlations between observable changes in FC and behavioral improvements. We hypothesize that these changes in FC between time points would correlate with gains in behavioral outcomes and have significant effects that persist 1 month after BCI intervention.

**Methods Study Design**

This is a single-blinded, randomized controlled trial (RCT) using a parallel design to evaluate the effectiveness and safety of 4-week BCI-robot rehabilitation combined with intensive occupational therapy compared with hand robot alone and dose-matched occupational therapy. The participants are patients who suffered from stroke from 3 months to 1 year and will be randomly assigned to either the BCI
group (BG) or control robot group (RG). The assessors are blinded, but patients and all the therapists are not. Wolf Motor Function Test (WMFT, score from 0 to 75) will be used as the primary outcome measure, while, Fugl-Meyer Assessment (FMA, score from 0 to 66), its wrist and hand (FMA-WH) sub-score, shoulder and elbow (FMA-SE) sub-score will be served as secondary outcome measures. The measurements will be evaluated at four points: baseline, 10 sessions after training, 20 sessions after training, and one-month follow up after the intervention. The fNIRS will be examined at baseline and one-month follow up.

Participants and Recruitment

All participants will be recruited from the inpatient department of the Neurorehabilitation of Shanghai Yangzhi Rehabilitation Hospital (Shanghai Sunshine Rehabilitation Center), which is affiliated to Tongji University School of Medicine.

The inclusion criteria are (1) aged 18 years or not older than 80 years; (2) first time onset stroke patient diagnosed by computed tomography or brain MRI; (3) time from stroke onset to be more than 90 days and less than 1 year; (4) first ever stroke patients with upper extremity paresis and functional restriction in the upper extremities at Brunnstrom stage 1-5; (5) no loss of proprioception in paretic fingers; (6) passive range of motion greater than −10 degrees for metacarpophalangeal joint extension; (7) ability to flex the paretic fingers passively; (8) ability of the patient to understand the study protocol; (9) MMSE score $\geq 21$ according to education level; (10) sign the written consent of the study;

The exclusion criteria are (1) with medical instability such as severe heart disease, uncontrolled hypertension, history of pulmonary embolism, acute pulmonary heart disease or severe pulmonary hypertension within 90 days before enrollment, severe hepatic or renal dysfunction, severe orthopedic impairment, and other serious medical conditions; (2) with severe cognitive disorder or/and MMSE score $< 21$ that the patient cannot follow and perform tasks; (3) with severe aphasia; (4) with limitation of passive range of motion in the paretic upper limb (dorsal wrist flexion $< 20^\circ$ limitation of elbow flexion $> 30^\circ$ and shoulder abduction $< 60^\circ$); (4) pacemaker or use of other implanted stimulators; (5) skull deformity that cannot record EEG; (6) participation in another clinical trial within 90 days before enrollment; (5) receiving other special neurorehabilitation techniques for upper extremity paresis such as transcranial magnetic stimulation, therapeutic electrical stimulation, CIMT, and repetitive facilitative exercise within 90 days before enrollment; (7) injection of botulinum toxin or anti-spasticity treatment of within 90 days before enrollment;

The recruiting physiatrists will screen the potential participants for eligibility. The patients then try the BCI-robot system to check the skin status and the BCI accuracy. If EEG could be recorded, the patient will be registered as an eligible participant. and the detailed procedures of this study will be explained to them. Lastly, written informed consent will be obtained from them.

Study Procedures

Fifty patients will be recruited in the next 1.5 years based on the calculation of the authors. Baseline assessments will be completed when the participants are eligible within 28 days. The first WMFT and
FMA assessments will be completed on the first day. And fNIRS will be done at the same day. Then 20 session trainings will be started on the second day and will be done on every weekday. The subsequent clinical scales evaluations will be completed after 10 sessions, 20 sessions intervention and one month follow-up. The fNIRS will be evaluated again at one month follow up. The possible adverse events will be collected from all the participants during the whole procedures. Study procedures are summarized in Trials diagram as follows (Table 1).

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<tr>
<th>Assessment</th>
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MMSE, Mini-Mental State Examination; BI, Barthel Index; MAS, Modified Ashworth Scale; WMFT, Wolf Motor Function Test; FMA-UE, Fugl-Meyer Assessment of Upper Extremity; FMA-WH, Fugl-Meyer Assessment of Wrist and Hand; FMA-SE, Fugl-Meyer Assessment of Shoulder and Elbow; fNIRS, Functional Near-infrared Spectroscopy

Randomization

Participants will be randomly allocated to the BCI-robot system group (BG) or the robot group (RG) using a computerized block randomization scheme.

Blinding

One qualified occupation therapist will be assigned to do all the assessments who will be blinded to treatment allocation and will not be involved in the participants’ treatment. Participants and all the physical therapists will not blinded to their own treatment.
BCI-robot system Intervention

MI-based BCI-robot training system (RHB-III with 16 EEG channels, Shenzhen Rehab Medical Technology Co., Ltd., China) is shown as follows (Fig. 1B). The whole system consists of three main parts: the collection system of real-time EEG signals, a central processing control algorithm, and a manus robot feedback. The real-time EEG signals recording locations are the same as the international 10/20 channel positions F1,Fz,F3,FC3,FC1,FCz,FC2,FC4,C3,C1,Cz,C2,C4,CP1,CPz,CP2 (Fig. 1A). EEG Recording Ag-AgCl electrode (φ = 9 mm) for EEG measurement is placed over the ipsilesional sensorimotor cortex, namely, C3 (for the left hemisphere) or C4 (for the right hemisphere). A ground electrode is placed on A1, and the reference electrode is placed on A2 (ipsilateral to the lesioned hemisphere). All electrodes are set manually and fixed with a custom-made headset. The central processing control algorithm amplify and process the real-time EEG signals after filter. Video clips on the computer screen are played to guide the participants to execute MI tasks. The external device is an exoskeleton robot hand which straps with the paretic hand to perform the real movement in grasping/opening tasks. A mu ERD (score from 0 to 100) is displayed to provide real-time visual feedback to achieve MI strategy. If the mu ERD score is below 60, the robot would not be triggered to move, which is considered to be a failed trial. The mu ERD score is then shown for 2 s. Participants are encouraged to instruct MI until successful or unsuccessful detection is indicated on the video screen. Task-Specific BCI Training session includes 4 runs of 40 trials, for a total of 160 trials, and an interrun break of 3 minutes. It takes about 40–50 min for each BCI training in total and 5 days per week, for 4 weeks.

On the control group, there is only the hand robot strapped with the paresis hand and there is no any BCI control the movement of the robot. We design a programm and make the hand robot move randomly for the matched training time.

Addition to the training system, all participants in the inpatient department receive 40 min of standard conventional occupational therapy per day, which consists of gentle stretching exercises, active muscle re-education exercises, and introduction to bimanual activities in their daily lives.

Functional Near-Infrared Spectroscopy Recording

A multichannel portable Functional Near-Infrared Spectroscopy (fNIRS) system, NirScan (NirScan-6000 USA) is utilized to explore the brain activity and analyze the FC by detecting the changes of concentration of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) of bilateral prefrontal and parital cortex. The sampling rate of the NIRS system was set to 10 Hz, and the wavelengths used are 740nm and 850nm. Head measurements are taken to ensure the placement accuracy of the fNIRS cap. The cap contains 6 sensors and 7 detector to record changes in blood oxygenation levels with a sampling rate of 10 Hz. The probe layout consists of 12 channels at 30mm spacing interval, with the arrangement of the channels compatible with that of the international 10–20 system [22]. The 12 channel montage configuration of the NIRS probe set is showed in Fig. 2. The optodes will be positioned over the primary motor cortex area (LMC: L1-L4; RMC: R5-R8); the prefrontal cortex area (LF: L9 and L10; RF: R11 and R12).
Prior to each recording, a NIR gain quality check will be performed to ensure whether data acquisition is moderate and neither under-gained nor over-gained. Briefly, at the start of each session, the participant sit quietly for nearly 5 seconds to make the signals stable, then the preparation finish and the signals are begun to record for 10 seconds for the rest-state recording time. The participants watch a 30-seconds video instruction of the kinesthetic motor imagery task, which consists of a “grasp a ball ” task and a “grasp a teacup ” task. Then the participants keep relax for 30 seconds. This process repeats two times for the tasking-state recording time is 180 seconds. The participants rest 30 seconds for the end. The total recording time is 220 seconds (see Fig. 3). To place the probes in a fixed position on the scalp, a head cap will be necessary to cover around the participant's head and be fixed with a trap to adjust and fixate the transmitters and receivers. In order to attain maximum efficiency of light coupling to the tissue, hairs needs to be carefully swept away to ensure the optodes touch the participant's skin tightly.

**Traditional rehabilitation and Recommendation**

Participants will be not allowed to undertake other specific intervention intending to improve hemiparesis (eg, CIMT therapy, NEMS, or other noninvasive brain regulation techniques such as transcranial magnetic stimulation or transcranial direct current stimulation) and botulinum toxin injection is also not allowed to hemiparetic upper limb during the 4-week period of intervention and follow-up. Standard medical care and traditional rehabilitation consists of routine physiotherapy and occupational therapy focusing on rehabilitation of functional transfer are available. But the participants are asked not to exceed the time and frequency during the intervention.

**Intervention Fidelity**

In this study, qualified Occupation therapists are trained and taken part in the training team with a high-level experience in BCI robot training for paresis. The research coordinator will manage the whole team members and randomly examine training sessions and evaluation sessions, to make sure that scheduled intervention will be performed accurately and with consistency to the study protocol proposed.

**Monitoring of Adverse Events**

Any adverse events including dizziness, fatigue, epilepsy attack and so on will be recorded in the electronic database of the study. And according to the policies of the hospital, referral of cases will be followed-up and recorded appropriate medical treatments.

**Criteria for Withdrawal**

Participants will be withdrawn from the study if any relevant deterioration happen in healthy issues likely to affect participation or if they want to withdraw their consent.

**The Primary Outcome Measurement**

The assessors are blinded, but patients and all the therapists are not. Wolf Motor Function Test (WMFT, score from 0 to 75) will be used as the primary outcome measure. ALL assessments are conducted at baseline (pre-), 10 sessions after intervention (mid-), 20 sessions after intervention (post-), and 4 weeks
after intervention (one month follow-up). EEGs is recorded by the EEG-BCI rehabilitation system during each training session.

### The Secondary Outcome Measurement

Measure Fugl-Meyer assessment Upper extremity motor function is assessed with the FMA (range 0–66 points, total score). FMA consists of four parts, Part A (shoulder/elbow/forearm: 36 points, A score), Part B (wrist: 10 points, B score), Part C (hand/finger: 14 points, C score), and Part D (coordination: 6 points, D score). FMA is assessed according to the scoring manual. The estimated clinically important difference of the FMA-UE scores ranged from 4.25 to 7.25 points in individuals with stable, mild to moderate upper extremity hemiparesis [23]. However, MCID for patients with severe hemiparesis remains to be shown. As a greater than 10% change in FMA motor scores may represent a clinically meaningful improvement based on clinical experience [24], MCID for severe hemiparesis may be lower than that for mild hemiparesis. A minimal detectable change of 3.2 points was reported in 31 patients with stroke [25].

Other measurements including the Barthel Index (BI, score from 0 to 100) which is one of the most frequently used measures to evaluate ADL in stroke research. The 10 assessed items of ADL are feeding, bathing, grooming, dressing, bowel control, bladder control, toilet use, transfers, mobility, and ascending and descending stairs. Modified Ashworth Scale Spasticity at the wrist and finger flexors of the affected upper extremity is also assessed with the Modified Ashworth Scale (MAS), a 6-point rating scale used to measure passive muscle resistance. In addition, we use the Mini-mental State Examination (MMSE, score from 0 to 30) for cognitive assessment. Higher scores indicate better cognitive function, and a score below 25 points is considered to be abnormal. Those above 21 points (according to education level) will be anticipated.

### Study Population and Setting

All patients will be recruited from the inpatient department of the Neurorehabilitation of Shanghai Yangzhi Rehabilitation Hospital (Shanghai Sunshine Rehabilitation Center) which is affiliated to Tongji University School of Medicine. Stroke will be diagnosed by two experienced attending physicians in the Neurology Department.

### Sample Size and Power Calculation

Repeated measures ANOVA with the Bonferroni post hoc test is performed at P = 0.05 (alpha) to compare the differences of clinical scales assessments between BG and RG. With the testing power of 80%, the significance level of 0.05 (two-sided), and a 1:1 ratio, with a dropout rate of 10%, a total of 50 patients are needed.

### Statistical Analysis

Continuous variables will be presented as mean ± SD or median with interquartile range (IQR). Categorical parameters are presented as independent proportions. Baseline information of patients in Brunnstrum stage and MMSE is compared using the Mann-Whitney U-test or t-test for continuous variables and
Fisher’s exact test or $\chi^2$ for categorical variables. Repeated measures ANOVA with the Bonferroni post hoc test is performed at $P = 0.05$ (alpha) to compare the differences of clinical scales assessments between BG and RG. Pearson correlation analysis will be utilized between the functional connectivity of the two groups. Data analysis will be performed using IBM SPSS (version 20.0) for Windows (SPSS Inc., Chicago, IL, USA). The Data and Safety Monitoring Board will conduct an interim analysis on 25 patients (half of the required sample size). $P < 0.05$ is considered statistically significant in the interim and final analyses.

**Ethics and Dissemination**

All participants provided voluntary written informed consent. Prospective participants were fully informed about what study participation involved and the potential benefits and risks. The study was conducted and approved by the Human Ethics Committee of Shanghai Yangzhi Rehabilitation Hospital (#SBKT-2021-044). Any protocol amendments will be submitted for ethical approval and communicated to the trial registry. After approval, the results will be presented at scientific meetings and published in journals.

**Results**

Recruitment started in June 2021 and had disrupted by the COVID-19 epidemic in Shanghai from March, 2022 to June, 2022. Now the recruitment restarted since July 1, 2022 as the status of the whole Shanghai city got better. This trial is currently in the data correcting phase. This RCT is expected to be completed by June 30, 2023.

**Discussion**

The previous studies have shown that patients post-stroke with severe hemiplegia can learn how to control external devices artificially then bypass the brain damage regions and re-animate paralyzed limbs after BCI training in motor functional recovery\(^{26–28}\). And one study reported that patients in spinal cord injury were learned to control a robotic arm combined with a computer cursor which performed spacious reach and grasp movements\(^{29}\). These advances are so excited and make us think it’s hopeful to utilize this new technique on stroke patients with little active flexion or extension movements in hemiplegic hand.

This clinical trial was designed to demonstrate the effect and safety of BCI-robot training system compared to simple hand robot on upper extremity recovery in stroke patients with severe dysfunction at subacute and chronic stage. To the date, although there were numerous research works have shown that robot system or BCI controlled system proved clinically important improvement on upper extremity function, the increase of activity of daily life has still limited because of the lack movements of wrist and fingers. In our study, we focused on the promotion of hand function and designed the hand robot in the whole rehabilitation system as the intervention strategy. Besides, fNIRS measurement has designed to record the brain activity and evaluate the changes of functional connectivity between the prefrontal cortices and the primary motor areas after the intervention and at one month follow-up to illuminate the possible mechanisms of BCI system. Previous scientific researchers suggested that the movements of
BCI controlled assistive prosthetic devices provided afferent and proprioceptive feedback to the somatosensory cortex which activated neuroplasticity and stimulated functional recovery. In this way neural network bypassed motor system disruption and new neural pathway built up[30–31].

We noted that this study has its own limitations. First, all the patients will be recruited from the same hospital and the same city (Shanghai), and there may be bias in patient selection. As there is no BCI-robot system and the same qualified therapists available in the similar rehabilitation hospitals, we haven’t designed multicenter clinical trials at the same time. Second, the sample of participants is relatively small, which might influence the likelihood of results. Third, we haven’t made a categories of etiology or lesions, which might also impact the differences of clinical outcomes.

In this RCT, we assessed a sufficient number of functional measures of the upper extremity including WMFT, FMA-UE, FMA-SE, FMA-WH, BI and MAS to make the outcomes of this RCT comparable with those of other trials. And it’s noteworthy that in this study it could be elicited whether motor-related circuits, including intra- and inter-hemispheric reorganization of somatosensory and motor-assemblies could be reinforced through BCI-robot rehabilitation system.

Abbreviations

ADL activities of daily living
BI Barthel Index
BCI brain-computer interface
CIMT constraint-induced movement therapy
EEG electroencephalogram
EMG electromyography
ERD event-related desynchronization
FMA Fugl-Meyer assessment
MAS Modified Ashworth scale
MCID minimal clinically important difference
RCT randomized controlled trial
UE upper extremity

Declarations
Acknowledgements

The authors would like to thank to all participants in the study: patients with stroke, their caregivers and occupational therapists.

Authors' contributions

All authors have made substantial contributions to the research design, data acquisition, to drafting the article or reviewing it critically, and all have approved the submitted version. Lingyu Liu and Liang Feng conducted the study, wrote the main manuscript text. Lingjing Jin designed the study and contributed to revision of the manuscript, Weizhen Wang trained the whole team members with the BCI system. Jing Wang designed BCI software application and documentation. Minxia Jin conducted the examination of fNIRS. Linguo Zhang, Qiuzhen Zhang and Xueying Qu contributed to participant recruitment and conducted the study. All authors read and approved the final manuscript.

Authors’ information

Prof. Lingjing Jin is the director of neurorehabilitation center of Shanghai Yangzhi Rehabilitation Hospital. His research focused on the pathological basis of abnormal neural regulatory circuits and the rehabilitative technologies for movement disorder. Lingyu Liu is a MD with research interest in BCI and neurorehabilitation. Liang Feng holds a PhD in neurology and is currently working on the neurorehabilitation. Xueying Qu, Qiuzhen Zhang and Linguo Zhang are Clinical physicians and and Clinical Consultant in stroke with research interest in all aspects of treatment. Prof. Jing Wang in Product Design has research interest in BCI hardware user informed design. Minxia Jin is an Occupational Therapist with an interest in research in novel technology based rehabilitation techniques. Weizhen Wang is a graduate in Rehabilitation Engineering with research interest in BCI, neuroengineering and neurorehabilitation.

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Availability of data and materials

Raw EEG data will be available from the authors on reasonable request.

Ethics approval and consent to participate

The study was conducted and approved by the Human Ethics Committee of Shanghai Yangzhi Rehabilitation Hospital (#SBKT-2021-044).

Consent for publication

Participants in Fig. 1 have signed consent to allow publication of these photos.
Competing interests The authors declare that they have no competing interests.

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References


**Figures**

![Figure 1](image)

**Figure 1**

Illustration of a Brain-Computer Interface (BCI)-robot system. (A) 16 EEG electrodes (circles filled with black color) used in our experiments. (B) Structural composition and experimental operation of BCI-robot system.
fNIRS configuration. 12 channels are designed in the study. The probes are located over prefrontal cortex (bilateral cortex near FPZ), the primary motor cortex (M1) (bilateral). The red circles represent the positions of sensors (S) and blue circles represent the positions of detectors (D). The lines between them are the channel. LMC: left M1 cortex; RMC: right M1 cortex; LF: left frontal cortex; RF: right frontal cortex.

Figure 2
Figure 3

fNIRS paradigm. There are two states of fNIRS testing, the rest state (RS) and the task state (TS).