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ORIGINAL ARTICLE

# Facilitating Effects of Transcranial Direct Current Stimulation on Motor Imagery Brain-Computer Interface With Robotic Feedback for Stroke Rehabilitation

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**Abstract**

**Objective:** To investigate the efficacy and effects of transcranial direct current stimulation (tDCS) on motor imagery brain-computer interface (MI-BCI) with robotic feedback for stroke rehabilitation.

**Design:** A sham-controlled, randomized controlled trial.

**Setting:** Patients recruited through a hospital stroke rehabilitation program.

**Participants:** Subjects (N = 19) who incurred a stroke 0.8 to 4.3 years prior, with moderate to severe upper extremity functional impairment, and passed BCI screening.

**Interventions:** Ten sessions of 20 minutes of tDCS or sham before 1 hour of MI-BCI with robotic feedback upper limb stroke rehabilitation for 2 weeks. Each rehabilitation session comprised 8 minutes of evaluation and 1 hour of therapy.

**Main Outcome Measures:** Upper extremity Fugl-Meyer Motor Assessment (FMMA) scores measured end-intervention at week 2 and follow-up at week 4, online BCI accuracies from the evaluation part, and laterality coefficients of the electroencephalogram (EEG) from the therapy part of the 10 rehabilitation sessions.

**Results:** FMMA score improved in both groups at week 4, but no intergroup differences were found at any time points. Online accuracies of the evaluation part from the tDCS group were significantly higher than those from the sham group. The EEG laterality coefficients from the therapy part of the tDCS group were significantly higher than those of the sham group.

**Conclusions:** The results suggest a role for tDCS in facilitating motor imagery in stroke.

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Stroke is a leading cause of serious disabilities in the United States.[1] Stroke survivors can partially recover their motor function control from rehabilitation that involves task-specific and repetitive motor exercises.[2] Since moving the stroke-impaired limb is often difficult or not possible, motor imagery (MI), the imagination of movements without physical execution, represents an alternative approach for rehabilitation.[3-5] However, while motor execution is observable, MI is a concealed mental process. Nevertheless, advances in brain-computer interface (BCI)

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technology have enabled stroke survivors to interact with the environment using their brain signals, and the technology seems to be effective in restoring impaired motor function.[6] Since neurophysiological phenomena called event-related desynchronization or synchronization (ERD/ERS)[7] are detectable from the electroencephalogram (EEG) during MI by healthy subjects[8] and most stroke patients,[9] EEG-based MI-BCI[10] can be used to objectively assess the performance of MI.[6] In addition, a recent clinical study[11] of chronic stroke patients who received BCI with hand and arm orthoses feedback showed greater motor improvements versus patients who received random feedback not linked to BCI. Hence, the use of MI-BCI presents a promising alternative approach for stroke rehabilitation.

Another promising development in stroke rehabilitation is the use of transcranial direct current stimulation (tDCS)[12,13] for neuromodulation and enhancement of motor recovery.[14] Facilitation of cortical excitability can be achieved with anodal stimulation, and inhibition with cathodal stimulation.[15] Both inhibition of excitability in the contralesional hemisphere by cathodal tDCS and facilitation of excitability in the ipsilesional hemisphere by anodal tDCS have been shown to improve motor performance in stroke.[16] Matsumoto et al[17] studied the modulation of ERD with anodal, cathodal, and sham tDCS in 6 healthy subjects performing right-hand MI. They found that the ERD of the mu rhythm in the frequency range of 8 to 13Hz (mu ERD) was significantly increased after anodal tDCS and was decreased after cathodal tDCS. Subsequently, Kasashima et al[18] investigated the modulation of ERD with anodal and sham tDCS in 6 hemiparetic stroke patients performing MI of the stroke-affected finger. They found a significant increase in mu ERD and suggested that tDCS can be used as a conditioning tool for BCI in stroke. In a preliminary study, Ang et al[19] reported no differences between the online MI-BCI accuracies of 3 stroke patients who received anodal and cathodal tDCS and 2 stroke patients who received sham tDCS, but the result was inconclusive because of the small sample size. In a recent investigation, Wei et al[20] studied the modulation of ERD with anodal and sham tDCS in 32 healthy subjects performing left- and right-hand MI. They found that the anodal tDCS induced ERD pattern changes in the upper mu (10−14Hz) and beta (14−26Hz) components.

While studies have demonstrated motor improvements in stroke patients[16] and an increase in mu ERD in healthy[17] and stroke patients using tDCS,[18] the use of tDCS to facilitate the ability of stroke patients to operate MI-BCI and subsequently the efficacy of tDCS on MI-BCI in poststroke motor recovery have not been investigated. To our knowledge, no randomized controlled study has previously investigated the effects of tDCS on the ability of stroke patients to operate MI-BCI for stroke rehabilitation. In this study, we investigated the clinical efficacy of tDCS and sham tDCS on MI-BCI with robotic feedback for stroke rehabilitation. We also investigated whether tDCS and sham tDCS could facilitate the stroke patients' performance of MI by studying the online MI-BCI accuracies of detecting MI of the stroke-affected upper limb versus the idle condition. We also studied the laterality coefficient of the mu ERD during MI-BCI with robotic feedback rehabilitation therapy of the stroke patients who received tDCS compared with those who received sham.

***List of abbreviations:***

| | |
|---|---|
| **BCI** | **brain-computer interface** |
| **EEG** | **electroencephalogram** |
| **ERD** | **event-related desynchronization** |
| **ERS** | **event-related synchronization** |
| **FBCSP** | **Filter Bank Common Spatial Pattern** |
| **FMMA** | **Fugl-Meyer Motor Assessment** |
| **MI** | **motor imagery** |
| **tDCS** | **transcranial direct current stimulation** |

# Methods

## Ethics statement

Ethics committee approval was obtained from the National Healthcare Group Domain Specific Review Board.

## Study design

This randomized controlled trial was conducted from January 1, 2011, to January 1, 2014, and involved subjects aged 21 to 70 years who had their first-ever subcortical stroke at least 9 months before recruitment, with moderate to severe impairment of upper extremity function (subscore of the Fugl-Meyer Motor Assessment [FMMA], 11−45). Since spontaneous recovery plateaus 6 months after stroke onset,[21] motor improvements observed in subjects 9 months poststroke would most likely be due to the study intervention assigned and not from spontaneous recovery. In addition, subjects with moderate to severe impairments were recruited because they had greater difficulty with motor execution and hence fewer therapeutic options.[22] Figure 1 shows a flow chart of the trial. Exclusion criteria included a history of seizures, major depression, and implants that may be triggered, moved, or heated by electrical current (eg, intracranial shunts, pacemakers, metal cranial implants). Depression was evaluated using the Beck Depression Inventory,[23] a 21-item questionnaire commonly used to assess poststroke depression.[24]

## EEG data acquisition

In this study, EEG data from 27 channels (fig 2) were collected using the Neuroscan Nuamps EEG amplifier[a] with unipolar Ag/AgCl electrodes channels, digitally sampled at 250Hz with a resolution of 22 bits for voltage ranges of ±130mV. The electrode impedance was kept below 5kΩ. EEG recordings from all channels were bandpass filtered from .05 to 40Hz by the acquisition hardware.

## MI-BCI screening

Since not all stroke patients could operate EEG-based MI-BCI,[9] the patients recruited in this study first underwent an MI-BCI screening session. In the screening session, a total of 160 trials of EEG that randomly comprised 80 MI condtions of the stroke-affected upper limb and 80 idle conditions were collected. The stroke patients' abilities to operate MI-BCI were then evaluated based on the 10×10-fold cross-validations of the 160 trials of data collected using the Filter Bank Common Spatial Pattern (FBCSP) algorithm[25] without any removal of artifacts such as the electro-oculogram. This analysis was performed similarly to the screening session reported by Ang et al.[9] Subjects with MI-BCI classification accuracy >58% were then recruited for randomization.

## Randomization and blinding

Subjects who passed BCI screening were checked to ensure that they were not enrolled in other clinical trials or receiving any other

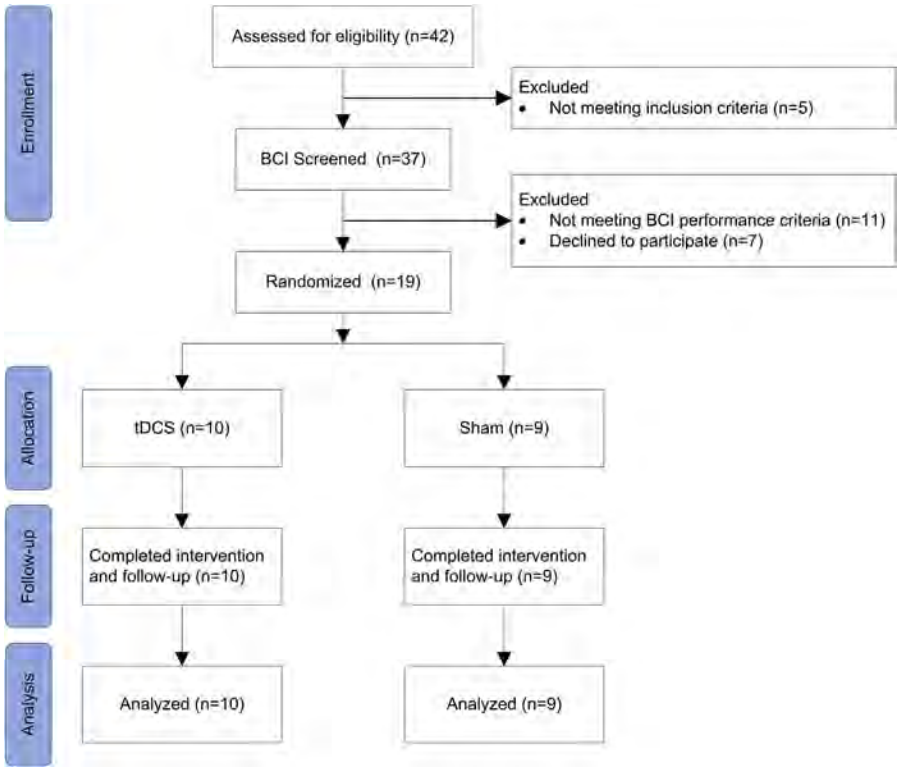


**Fig 1** Consolidated Standards of Reporting Trials flow diagram.

therapeutic activities aimed at improving stroke-affected upper limb function. Subsequently, subjects who passed and gave further consent were randomly assigned to receive either the tDCS or the sham-tDCS intervention. Figure 3 shows the setup for the tDCS and sham interventions. Subjects in both groups first underwent a calibration session in which their stroke-affected upper limb was strapped to the MIT-Manus robot.[b] A total of 160 trials of EEG data that comprised 80 MI of the stroke-affected upper limb and 80 idle condition were collected in a similar manner to that in the screening session. Subsequently, the subjects in both groups underwent 10 rehabilitation sessions for 2 weeks, 5 times a week. Each rehabilitation session comprised 20 minutes of stimulation with tDCS or sham tDCS, followed by 8 minutes of evaluation and 1 hour of therapy using EEG-based MI-BCI with robotic feedback.

## MIT-Manus robot

The MIT-Manus is a robot with 2 degrees of freedom that provides horizontal elbow and forearm reaching exercises using an 8-point clock-face—drawing interactive video game.[26] In this study, the stroke-affected upper limb of subjects from both groups was strapped to the Manus robotic exoskeleton. The subjects were instructed to imagine moving their stroke-affected hand toward the target indicated on the 8-point clock-face video game. They were also instructed to continue MI until successful or unsuccessful detection was indicated on the video screen. Voluntary movements during MI were restricted by locking the mobility of the Manus robot. If MI was successfully detected, visual and movement feedback was provided by the Manus robot through passive movement of the stroke-affected arm from the center toward the target displayed on the screen and back to the target along a predetermined robotic trajectory.[26] This robotic movement forms a proprioceptive afferent feedback that closes the loop in providing a reward for performing MI.[27,28]

## Transcranial direct current stimulation

Direct current was applied for 20 minutes using a saline-soaked pair of surface sponge electrodes from a battery-operated constant current stimulator[c] at an intensity of 1mA with the anode placed over the M1 motor cortex of the ipsilesional hemisphere and the cathode placed over the contralesional M1. The M1 positions for the tDCS electrodes were located at channels C3 and C4 shown in figure 2. The goal of this montage was to decrease cortical excitability in the unaffected motor cortex and to increase it in the affected motor cortex.[29,30] For the sham intervention, the current was applied only for the first 30 seconds of the 20 minutes to give the sensation of the stimulation. This duration was established in several studies[29,30] to be effective in blinding subjects to the assigned intervention[31] without altering cortical excitability.

## Quantification of motor improvements

The total FMMA score (range, 0—66) on the stroke-impaired upper extremity was used to measure the motor improvements in this study. The outcomes were measured at 3 time points: at baseline (wk 0), at completion of intervention (wk 2), and at a 2-week follow-up (wk 4).

## Quantification of online MI-BCI performance

The calibration session consisted of 4 runs of 40 trials each for a total of 160 trials, and an interrun break of at least 2 minutes was provided after each run (fig 4A). Each run randomly comprised 20 trials of MI of the stroke-affected upper limb and 20 trials of the

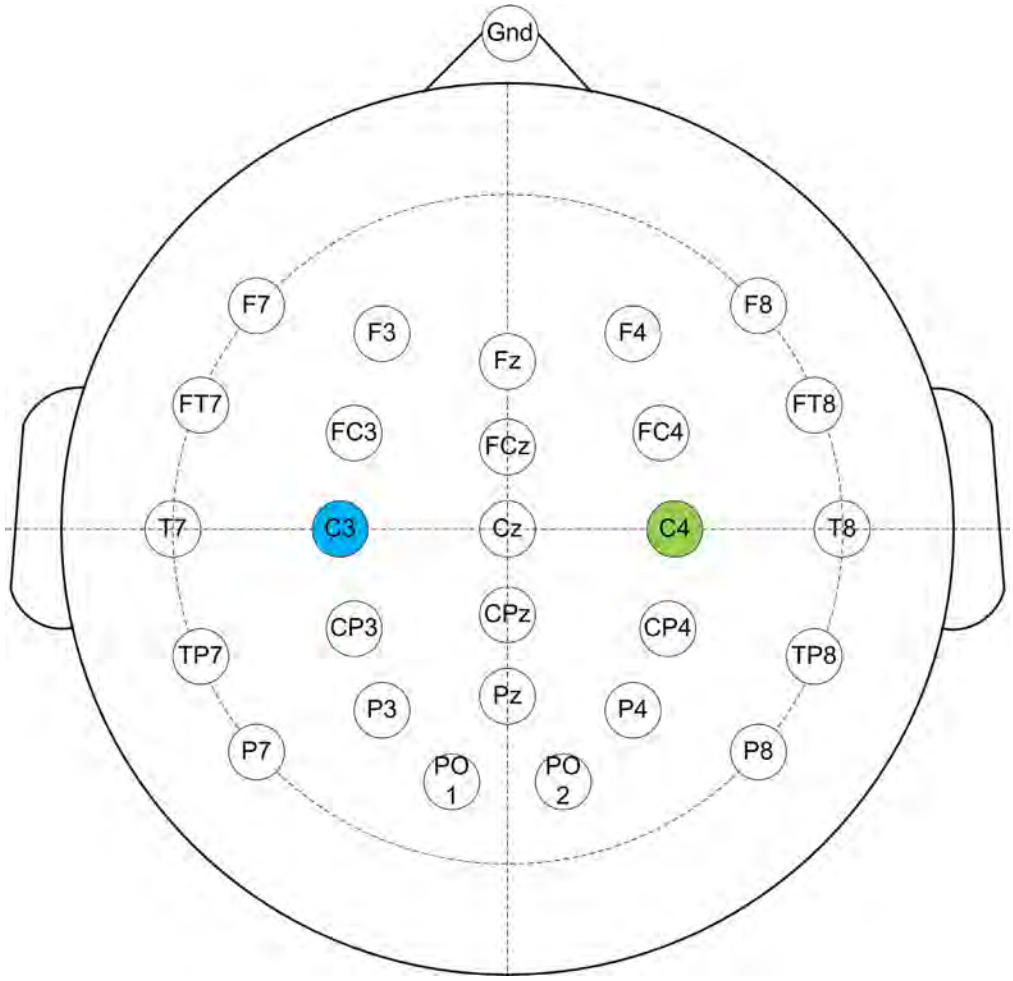


**Fig 2** Positions of EEG channel locations. The reference electrode is located on the nasion. Channels on the left and right hemisphere for offline ERD analysis are labeled *blue* and *green*, respectively. Abbreviations: C, central electrodes; CP, centroparietal electrodes; F, frontal electrodes; FC, frontocentral electrodes; FT, frontotemporal electrodes; Gnd, ground electrode; P, parietal electrodes; PO, parieto-occipital electrodes; T, temporal electrodes; TP, temporal-posterior electrodes; z, electrode in midline.

idle condition. Each trial lasted approximately 12 seconds, and each run lasted approximately 8 minutes. The calibration session lasted approximately 1 hour inclusive of EEG setup time. A visual cue was used to prepare the subject, and subsequently another cue was used to randomly instruct the subject to perform either MI or the idle condition. The EEG segment of 0.5 to 2.5 seconds from the instruction cue was then extracted to train a subject-specific MI detection model using the FBCSP algorithm.[25] No robotic feedback was provided in the calibration session.

The rehabilitation session comprised an evaluation portion and a therapy portion. The evaluation portion consisted of 40 trials that randomly comprised 20 trials of MI of the stroke-affected upper limb and 20 trials of the idle condition (fig 4B). Similar to the calibration session, a visual cue was used to prepare the subject, and subsequently an instruction cue was provided. The EEG segment of 0.5 to 4.5 seconds from the instruction cue was then extracted to classify the EEG segment to perform online detection of MI or the idle condition using the FBCSP algorithm.[25] Once MI was detected, the robot was triggered to provide a feedback. The online accuracy of the evaluation portion of the rehabilitation session was then recorded based on the detection of MI or the idle condition compared with the instruction provided.

## Quantification of ERD

The therapy portion of each rehabilitation session consisted of 4 runs of 40 trials each for a total of 160 trials, and an interrun break of 3 to 5 minutes was also given after each run (see fig 4B). Each trial lasted approximately 17 to 19 seconds, and each run lasted approximately 13 minutes. Similar to the evaluation part of the rehabilitation session, prepare and instruction cues were provided to the subject. The EEG segment of 0.5 to 4.5 seconds from the instruction cue was then extracted to classify the EEG segment to perform online detection of MI. Once MI was detected, the robot was triggered to provide a feedback. The EEG segment of 0 to 8 seconds from the prepare cue was then extracted to perform offline ERD analysis.

ERD values in the offline EEG analysis were estimated from the change in the band power in the frequency band of the mu rhythm (8−13Hz) from the left (C3) and right (C4) channels in the 2- to 6-second segment relative to a baseline of the −1.5- to 0-second segment, whereby the time is relative to the instruction cue. This time segment was selected to encompass the MI period performed by the subjects. The following method was used to compute the ERD strength value for each left and right channel:

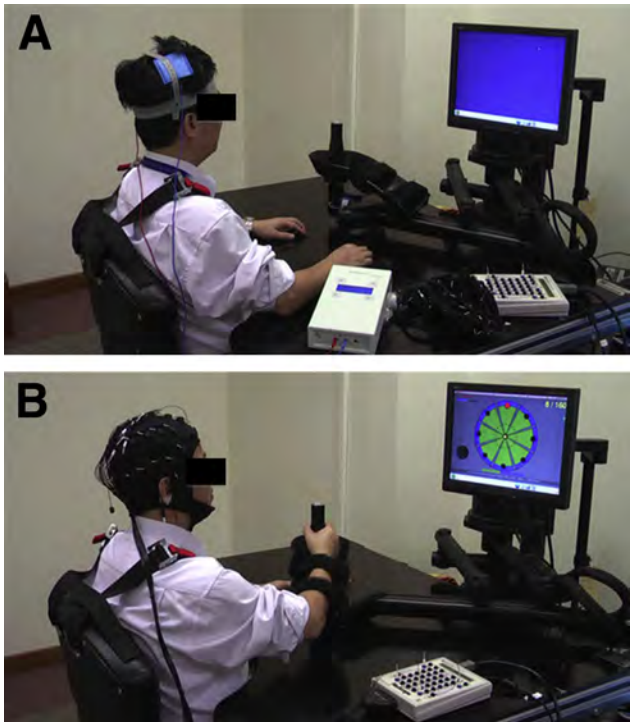


**Fig 3** Setup of (A) tDCS and (B) EEG-based MI-BCI with robotic feedback rehabilitation for stroke in a local hospital. The same setup is used for sham.

1. Bandpass filtering of 8−13Hz on the EEG time segment −2 to 6 seconds relative to prepare cue for all 160 trials in the therapy part of the rehabilitation session.
2. Squaring the bandpass-filtered samples to obtain power samples.
3. Average power samples across all trials.
4. Compute power of baseline from average on time segment −1.5 to 0 seconds.
5. Compute ERD/ERS strength values of channel $j$ on time segment 2 to 6 seconds using the following equation[7]:

$$S_j(t) = \frac{A_j(t) - R_j}{R_j} \times 100 \quad (1)$$

where $A_j(t)$ is the averaged power sample of time sample $t$ of channel $j$ from step 3, and $R_j$ is the averaged power of baseline of channel $j$ from step 4.

6. Compute the ERD strength value from the sum of the negative values for time samples $t$ from 2 to 6 seconds of channel $j$ using the following equation:

$$E_j = \sum_{t \in [2,6]} \left(S_j(t) \mid S_j(t) < 0\right) \quad (2)$$

The above method of computing the ERD strength followed closely the procedure provided by Pfurtscheller et al.[7] ERD values were defined as negative relative to the baseline, whereas ERS strength values were defined as positive.[7] As such, only negative values were included in the ERD analysis.

A laterality coefficient was then computed to assess the hemispheric asymmetries of the ERD pattern using the following equation:

$$L = \frac{E_c - E_i}{E_c + E_i} \quad (3)$$

where $E_c$ and $E_i$ denote the ERD strength value of the channel that is contralateral and ipsilateral to the stroke-affected hand, respectively.

The laterality coefficient was used by Kaiser et al[32] to investigate hemispheric asymmetries of ERD and ERS in stroke. A positive or negative $L$ indicates higher or lower values, respectively, in the hemisphere contralateral to the stroke-affected hand.

## Statistical analysis

Analysis of variance was used to examine the demographic and baseline group differences. Two-sided $t$ tests were performed to analyze for significant motor improvements at weeks 2 and 4 from baseline (week 0) for the tDCS and sham groups. Analysis of covariance was used to examine the group differences at each time point between the 2 groups after adjusting for baseline differences. To compare the performance of MI-BCI and the ERD laterality coefficient between the 2 groups, the $P$ value of 2-samples $t$ test was computed between the subjects from the evaluation and therapy part of the 10 rehabilitation sessions, respectively. In this case, we assumed that the data collected in 1 session from a subject is independent of the data from another session collected

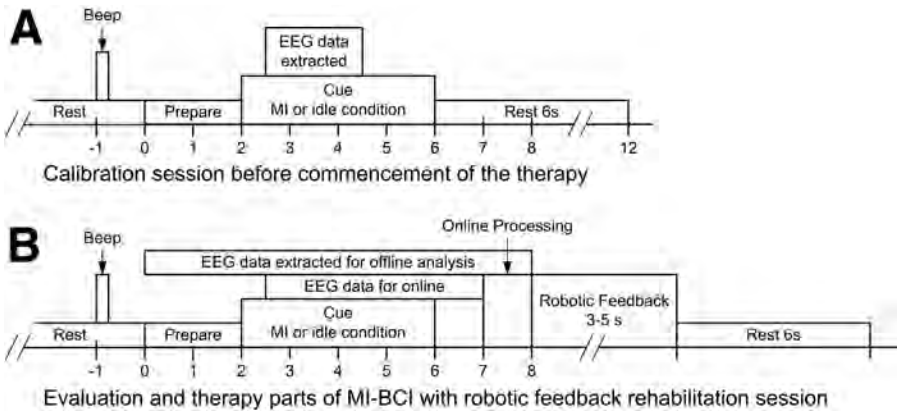


**Fig 4** Acquisition of EEG for online and offline analysis. (A) Timing of the motor imagery of the stroke-affected hand or background rest tasks for the calibration session before commencement of the therapy. (B) Timing of the motor imagery of the stroke-affected hand using online MI-BCI with robotic feedback for the rehabilitation session.

**Table 1** Demographics and baseline characteristics by intervention

| Variable | Total (N = 19) | Intervention | |
|---|---|---|---|
| | | tDCS (n = 10) | Sham (n = 9) |
| Age (y) | 54.1±10.6 | 52.1±11.7 | 56.3±9.5 |
| Sex | | | |
| Male | 14 (73.7) | 6 (60.0) | 8 (88.9) |
| Female | 5 (26.3) | 4 (40.0) | 1 (11.1) |
| Stroke type | | | |
| Infarction | 13 (68.4) | 6 (60.0) | 7 (77.8) |
| Hemorrhage | 6 (31.6) | 4 (40.0) | 2 (22.2) |
| Stroke nature | | | |
| Cortical | 1 (5.3) | 1 (10) | 0 (0) |
| Subcortical | 18 (94.7) | 9 (90) | 9 (100) |
| Affected limb | | | |
| Right | 11 (57.9) | 5 (50.0) | 6 (66.7) |
| Left | 8 (42.1) | 5 (50.0) | 3 (33.3) |
| CVA to intervention (d) | 1037±598 | 1052±722 | 1021±465 |
| BCI screening | 75.6±10.4 | 79.1±9.4 | 71.7±10.7 |
| FMMA at week 0 | 34.0±7.9 | 35.3±7.8 | 32.6±8.1 |

NOTE. Values are mean ± SD or n (%).
Abbreviation: CVA, cerebrovascular accident.

on a different day. The justifications for this assumption are as follows:

1. The stimulation of a session on a subject is independent of other sessions for the same subject, since it has been shown that motor cortical excitability increases for up to 90 minutes after the end of stimulation.[33]
2. The performance of MI-BCI and the ERD laterality coefficient of 1 session from a subject is independent of other sessions for the same subject, since there is inherent nonstationarity in the EEG across sessions recorded on different days from the same subject.[34]

# Results

## Patients

Twenty-six of 37 recruited patients passed the screening sessions, and 19 gave further consent and were recruited for randomization, with 10 and 9 patients allocated to the tDCS group and sham group, respectively. Details on the demographics of the patients are shown in table 1. There were no significant baseline differences in the 2 groups in terms of age ($P = .40$), sex ($P = .17$), stroke type ($P = .43$), stroke nature ($P = .36$), affected limb ($P = .49$), time from cerebrovascular accident to intervention ($P = .91$), BCI screening ($P = .13$), and FMMA at week 0 ($P = .46$).

## Motor improvements

Table 2 shows the FMMA score measured at weeks 0, 2, and 4 for the tDCS and sham groups. No significant FMMA score gains at week 2 compared with baseline at week 0 were observed (tDCS group: 0.9±3.0, $P = .36$; sham group: 2.8±4.0, $P = .07$). At week 4, significant FMMA score gains compared with baseline at week 0 were observed (tDCS group: 5.0±4.4, $P = .006$; sham group: 5.4±5.7, $P = .02$).

**Table 2** Efficacy measures by FMMA scores for tDCS (n = 10) and sham (n = 9) groups

| Outcome | Group | Baseline | Improvements Relative to Week 0 | |
|---|---|---|---|---|
| | | Week 0 | Week 2 | Week 4 |
| Upper extremity (0∼66) | tDCS | 35.3±7.8 | 0.9±3.0 | 5.0±4.4 |
| | Sham | 32.6±8.1 | 2.8±4.0 | 5.4±5.7 |

No significant intergroup differences were observed at any time point during the study after adjusting for the baseline FMMA score at week 0 (wk 2: $P = .243$; wk 4: $P = .874$).

## Online MI-BCI performance

Figure 5 shows a plot of the averaged online accuracies of detecting MI versus the idle condition for the tDCS and sham groups across the evaluation part of the 10 rehabilitation sessions. The results showed deviation of online accuracies across subjects and sessions, and the averaged accuracies of the subjects from the tDCS group across most of the 10 rehabilitation sessions are higher than those of the subjects from the sham group. The averaged accuracy of classifying the MI of the stroke-affected upper limb versus the idle condition across the evaluation part of the 10 rehabilitation sessions from the tDCS group (62.9%) is significantly higher than that from the sham group (57.0%, $P = .002$).

## ERD laterality coefficient

Figure 6 shows a plot of the averaged ERD laterality coefficient of the therapy part of the rehabilitation sessions for the tDCS and sham groups. The results again showed deviation of the ERD laterality coefficient across subjects and sessions, and the averaged ERD laterality coefficients of the subjects from the tDCS group across most of the 10 rehabilitation sessions are higher than those of the subjects from the sham group. The averaged ERD laterality coefficient of the therapy part of the 10 rehabilitation sessions from the tDCS group (.050) is significantly higher than that from the sham group (−.063, $P = .016$).

# Discussion

This study presents the results from a clinical study that investigated the effects of tDCS on EEG-based MI-BCI with robotic feedback compared with sham for upper limb stroke rehabilitation. Since motor cortical excitability has been shown to increase for up to 90 minutes in subjects who receive tDCS,[33] we investigated whether tDCS would facilitate motor improvements and MI performance in stroke patients undergoing MI-BCI with robotic feedback rehabilitation.

There were no significant motor improvements observed upon completion of 2 weeks of intervention in both the tDCS and sham groups. The results from a recent randomized controlled trial[4] yielded a similar average FMMA score improvement of 1.1 in 11 stroke patients after 2 weeks, but it increased to 4.5 after completing 4 weeks of MI-BCI with MIT-Manus robotic feedback intervention. The results from another recent randomized controlled trial[35] yielded a significantly higher FMMA score improvement of 7.2 in 6 stroke patients after completing 6 weeks

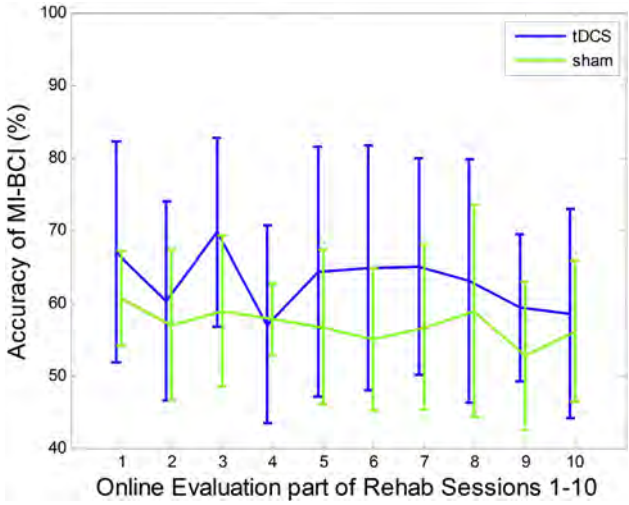


**Fig 5** Plot of the online accuracies of detecting MI of the stroke-affected hand versus the idle condition for the tDCS and sham groups during online evaluation part of the rehabilitation sessions. Accuracies are computed online by performing session-to-session transfer using the FBCSP algorithm trained on data from the calibration session to the evaluation part of each of the 10 rehabilitation sessions. Horizontal axis represents the 10 rehabilitation sessions the patients underwent. Vertical bar plots the SDs across subjects in each group.

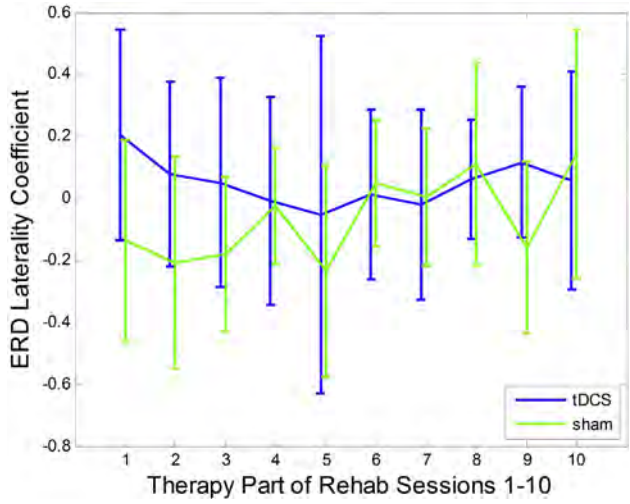


**Fig 6** Plot of the averaged ERD laterality coefficient of the therapy part of the rehabilitation sessions for the tDCS and sham groups. Vertical axis represents the ERD laterality coefficient computed by averaging the ERD computed from 0 to 8 seconds of EEG of all 160 trials of the MI-BCI with robotic feedback rehabilitation. Horizontal axis represents the 10 rehabilitation sessions the patients underwent. Vertical bar plots the SDs across subjects in each group.

of MI-BCI with the Haptic Knob robot for arm rehabilitation, compared with an improvement of 4.9 in 7 patients who received 6 weeks of standard arm therapy. The results from these studies indicate that the 2 weeks of intervention in this study may be too short to observe significant motor improvements. As a whole, no intergroup differences were found, which suggests that there may be no additional benefit in adding tDCS to the MI-BCI training. However, this warrants further investigation because of the short intervention in this study.

The results of the therapy part of each rehabilitation session showed that the ERD laterality coefficient of subjects in the tDCS group was significantly higher than that of subjects in the sham group. Since the SDs were large, the significant differences observed were most likely from the first 3 sessions. A higher positive ERD laterality coefficient indicated higher ERD strength values in the ipsilesional hemisphere that is contralateral to the stroke-affected hand. The result is also consistent with studies[17,18,20] that show a significant increase in mu ERD after tDCS compared with sham. The mechanism of ERD is thought to be due to a decrease in synchrony of the underlying neuronal population.[7] Since anodal tDCS increases cortical excitability of the ipsilesional M1,[15] tDCS may result in more activated desynchronized neurons when MI is performed.[18]

The results from the evaluation part of each rehabilitation session showed that the averaged online accuracy of MI-BCI from subjects in the tDCS group was also significantly better than that from subjects in the sham group. Although the results showed large deviations across subjects and across sessions, the results indicated that there is a significant effect of tDCS in improving the online accuracy of MI-BCI performance compared with sham. This significant improvement in online accuracies correlates with the higher positive ERD laterality coefficient observed because the FBCSP algorithm[25] used in this study performed spatial filtering to discriminate mental states that are characterized by ERD and ERS.[36] In the study by Wei,[20] only a slight increase in averaged online accuracy of MI-BCI between pre- and postanodal tDCS in healthy subjects was reported, but no significant difference was found despite a significant increase in ERD observed. In contrast, significant improvement in online accuracy is observed in this study, which may be due to the relatively lower baseline ERD of stroke patients compared with healthy subjects.[18] The ERD may also be underestimated in this study because it was quantified on a trial-wise basis by comparing postcue segments to precue segments. This is because the subjects may be anticipating the cue, thereby causing some ERD in the precue segment and diluting the effect in the postcue segment.

The results of the online accuracy of MI-BCI from subjects in both groups showed a trend of deterioration over time. Since only an initial calibration session was used to train the subject-specific MI detection model in this study, the deterioration may be due to the increasing session-to-session transfer nonstationarity[37] when the FBCSP algorithm[25] was used to detect MI in sessions that were days apart from the training session. Therefore, adaptation methods[37,38] are recommended to address this issue in future studies.

## Study limitations

The limitations in our study are its small sample size, the heterogeneity within subjects, and the assumption of independence in the statistical test of the data collected from the same subject for the 10 rehabilitation sessions. If the data collected from the same subject across the 10 rehabilitation sessions were assumed to be dependent, a repeated-measure analysis of variance would have to be performed. Performing this analysis would yield $P$ values of .19 and .15 for the online MI-BCI performance and ERD laterality coefficient, respectively, between the tDCS and sham groups. These results are then not statistically significant because of the reduction of the sample size for analysis.

Finally, the clinical study also collected secondary outcome measures such as resting motor threshold using transcranial magnetic stimulation,[39] grip strength,[40] the Box and Block Test,[41] and neuroimaging pre- and posttherapy for the tDCS and MI-BCI with robotic feedback stroke rehabilitation compared with sham. Detailed results of the secondary outcome measures and the analysis of the neuroimages will be reported in separate articles.

## Conclusions

Although studies have shown a significant increase in mu ERD from the EEG in healthy subjects[17] and stroke patients,[18] we investigated whether 20 minutes of tDCS or sham stimulation prior would have a significant effect on 1-hour rehabilitation sessions of MI-BCI with robotic feedback rehabilitation. We performed a randomized controlled trial and collected data from 19 chronic stroke patients with moderate to severe upper extremity functional impairment who underwent 10 sessions of intervention, each consisting of 8 minutes of evaluation and 1 hour of therapy. We found that the addition of tDCS did not result in additional motor improvements compared with sham. Nevertheless, we found that the averaged online accuracy of the evaluation part and the averaged ERD laterality coefficient of the therapy part for subjects who underwent tDCS were significantly higher than for those who received sham. Hence, the results suggest a role for tDCS in facilitating MI in stroke. The facilitation of MI may translate to enhanced sensorimotor integration and the efficacy of MI-BCI as a tool for motor recovery after stroke. It may also avail MI-BCI to stroke patients who initially fail the screening test for the ability to operate MI-BCI. However, further investigations are necessary on a larger sample with a longer intervention period.

## Suppliers

a. Neuroscan Nuamps EEG Amplifier; Compumedics USA, Compumedics Neuroscan and Compumedics DWL.
b. MIT Manus Robot; Interactive Motion Technologies.
c. neuroConn DC Stimulator; neuroConn GmbH.

## Keywords

Brain-computer interfaces; Rehabilitation; Stroke

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