Digital Mirror Box: An interactive hand-motor BMI rehabilitation tool for stroke patients

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***Abstract*— We develop a brain-machine interface for the hand-motor rehabilitation of stroke patients. The interface provides both visual and proprioceptive feedback to the user based upon the successful generation of cortical motor commands. We discuss the details of the proposed system and provide a summary of the preliminary experiment. The experiment investigates the importance of simultaneous visual and proprioceptive feedback to the delivery of motor commands from the affected motor cortex of the patients. We also discuss a case study involving a chronic stroke patient who trained with the system for 14 days to recover functional movement in the hand. The results obtained by this study suggest that the developed system is effective at accelerating the recovery of motor function in stroke patients with hand paralysis.**

I. INTRODUCTION

Stroke usually causes hand paralysis, which affects the quality of life of the patient. Injuries in the hand motor area of the cerebral cortex, or other areas in the motor pathways of the brain, disrupt the communication of hand motor commands to the peripheral muscles. This causes paralysis in the affected hand. Paralysis causes spasms (fixed muscle and joint) and/or atrophy of muscles, which further limits the activities of daily living (ADL). Therefore, an appropriate and effective rehabilitation for reestablishing lost motor pathways is required to regain motor function in the affected hand. Conventional physical or occupational therapy trains patients to use their affected hand intensively to stimulate the affected brain hemisphere and to encourage reorganization of the motor pathway. Therapists guide the affected hand and assist patients with achieving specific hand motions by providing various sensory stimuli including proprioception. Proprioception is a sense of position of one's own body parts [1] derived from proprioceptors in skeletal muscles, tendons, and joints. Proprioceptive feedback, also defined as the feeling of body motion by oneself, is generated by either passive or active manipulation of the corresponding body parts [2, 3]. During physical or occupational therapy, the motor intent of the patient and the corresponding visual and proprioceptive feedback are considered important in facilitating body ownership and reorganization [4, 5]. However, it is difficult for therapists to guide hand movement that synchronize with the invisible intentions of a patient's movements.

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Recent advancements in functional neuroimaging techniques have opened up a potential application for the brain-machine interface (BMI). This application would allow for accelerated rehabilitation by binding motor commands from an injured brain to actual visual feedback [6] or/and proprioceptive feedback using exoskeleton robots attached to a paralyzed hand or arm [3, 7-10]. Most stroke rehabilitation systems use event-related desynchronization (ERD) to return image-related motor feedback to the patients. ERD is a suppression of the μ band (8 – 13 Hz) activity found around motor cortices during imaging or actually moving body parts, and represents the active state of the motor cortex [11]. The goal of BMI rehabilitation is to increase the ERD of the affected hemisphere in the patient to the point where they would convey motor intent directly to their paralyzed hand.

The studies referenced previously reported the effectiveness of ERD-BMI on motor rehabilitation for stroke patients [3, 6-10]. The results were confirmed through functional and structural measurements of cortical motor pathways [7] as well as through physical assessments, such as the Fugl-Meyer assessment (FMA) [8]. However, Gregg et al. [12] reported that an individual difference appears in the ability of motor imagery. De Beni [13] also reported that the age of the participant affects their ability to generate motor intent. There is a possibility that stroke patients may have difficulty performing motor imagery due to their advanced age and an impaired working memory function of body motor image, which is required to induce ERD without motor execution. In fact, many stroke patients have difficulty in performing motor imagery by mere verbal instruction in clinical practice. The dependence on the participants' ability to generate ERD may limit the use of ERD-based BMI rehabilitation [14], and a more reliable method for facilitating ERD may be required.

Therefore, we developed an ERD-BMI rehabilitation device called the digital mirror box (DMB) [15]. This device integrates the action observation paradigm with the ERD-based BMI. Action observation is one of the most promising methods for promoting motor imagery. Observing body action utilizes a similar distribution of motor neurons, which are responsible for executing the observed action (mirror neuron system [16]). Several studies demonstrated the reliability of action observation to facilitate corticomotor excitability [17] and improve upper limb function of stroke patients with paralysis [18, 19]. We have previously shown that hand action observation in a motor imagery paradigm with a first-person perspective could robustly induce ERD responses from stroke patients with hand paralysis [15]. Another strategy for facilitating motor pathway development is to accurately synchronize the motor intent of the patient and the multimodal feedback from visual and proprioceptive stimuli in real-time. Previous ERD-BMI rehabilitation systems provided sensory feedback once the ERD strength exceeded a predetermined threshold value during several seconds of a motor imagery period [3, 6-10]. In these cases, patients may repetitively imagine the action which is not time-locked to the imagery cue. This remains a possibility of a time lag between the actual timing of specific action imagery and that of sensory feedback. Therefore, we used visual stimulation of single hand action (grasping) to control the timing of motor imagery and give timing-specific feedback to the ERD response evoked by the imagery. To investigate the importance of motor imagery timing and sensory feedback to the patient, we conducted a single-session DMB trial to study the transition rate of the successful operation of ERD-BMI and the ERD strength in stroke patients when they received synchronous or delayed multimodal feedback. The DMB trial included 12 runs. We also discuss a case study involving a single patient that investigates the functional and neurophysiological effect of intensive 14-day training with the DMB.

II. Digital Mirror Box System details

Fig. 1 shows an illustration of the BMI training system using the DMB. In successful motor imagery, the DMB provides the user with synchronized somatosensory feedback via an exoskeleton robot attached to the user's hand and visual feedback via a tablet screen. BMI training consists of one session of offline training data collection and one session of online BMI operation.

A. *Training data collection*

The ERD response of participants during hand action observation was first collected to develop an individual classifier of motor imagery response. The participant sat in a chair and comfortably placed his/her affected forearm on the table. A tablet screen (ASUS Portable AiO P1801-T) was placed in front of the hand to be tested. Each trial (8 s; Fig. 2) began by displaying a black fixation cross on a white screen (preparation cue, 4 s) to remind the participant to relax and to pay attention to the side of the screen where a hand action movie would be presented. The fixation cross was followed by a 4 s movie of a moving hand to encourage the participant to formulate an image of the hand motion. We prepared two kinds movies to facilitate hand motor imagery. The first movie involved a hand grasping a tennis ball resting in its palm (hereinafter referred to as the 'stop' condition). The second movie showed a hand grasping a tennis ball that rolled into its palm (hereinafter described as the 'move' condition). Participants watched each movie 8 times in succession. We prepared the hand action movies for male and female hands. Patients watched the movies for their gender-matched hand to increase the perceived ownership of the hand shown on the screen.

EEG signals were recorded with the g.USBamp (g.tec Medical Engineering GmbH, Austria) EEG amplifier system. Nine electrodes were placed on the patients' scalps at the T7, C5, C3, C1, Cz, C2, C4, C6 and T8 locations, which are based on the international 10-10 system. These channels were

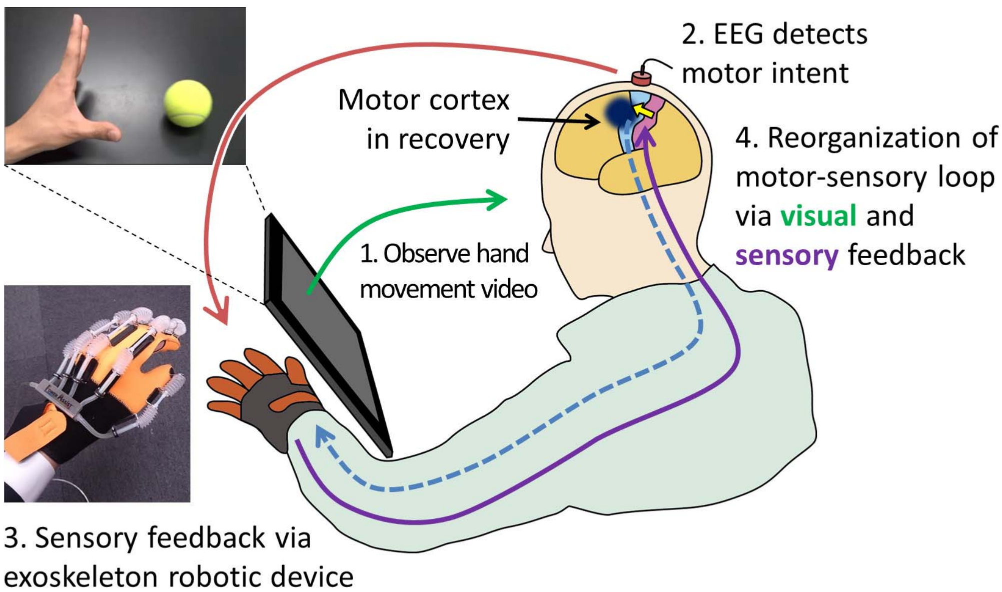

Fig. 1 Representation of the digital mirror box (DMB) for stroke hand rehabilitation.

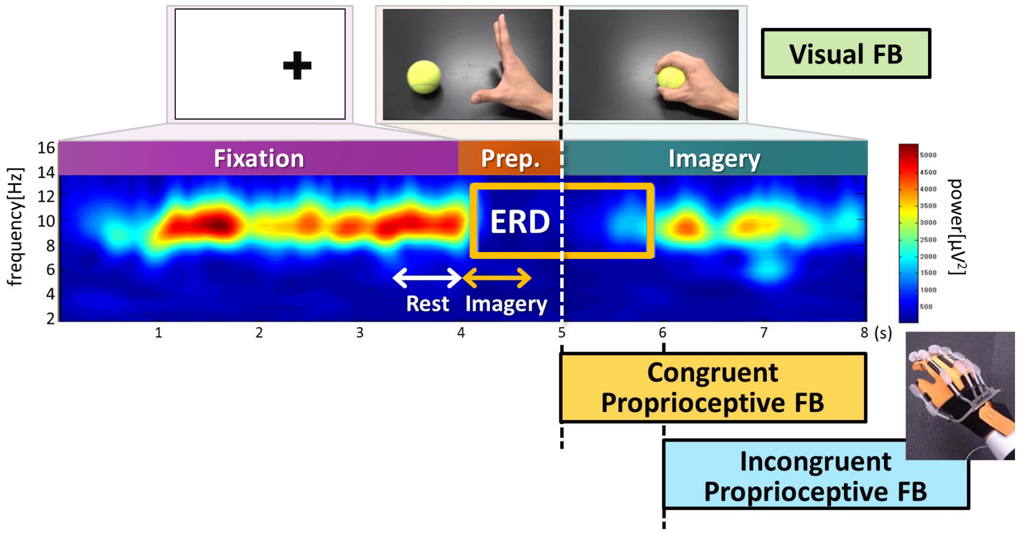

Fig. 2 Time-course representation of a single DMB trial.
A representative time-frequency power distribution of the EEG response from the corresponding motor area is presented. FB: feedback.

selected based on the coverage of the primary motor cortices. We set the sampling rate, band-pass filter, and notch filter to 256 Hz, 0.5 - 30 Hz, and 50 or 60 Hz, respectively. We extracted two 700 ms long samples of EEG data for the rest and imagery periods for each trial. The rest period corresponds to the EEG data recorded for 700 ms before the movie began. During the rest period, participants were asked to stare at the fixation cross to prevent body movement. The imagery period corresponds to the EEG data recorded for 700 ms immediately after the movie began (Fig. 2), in which participants were encouraged to imagine the hand motion. We calculated the power spectrum for 7-12 Hz of these two data sets using the fast Fourier transform method, and defined ERD strength with the following equation (1):

$$\text{ERD strength} = 100 \times (\mu\_rest - \mu\_task)/\ \mu\_rest\ [\%] \qquad (1)$$

where μ_rest and μ_task denote the μ band spectrum powers obtained during the rest and imagery periods, respectively. The specific frequency band of 7-12 Hz was selected by taking the grand average of the power spectrum density of the participants.

B. *Preparation for online session*

We chose the most appropriate single electrode to be used in the online session based on the characteristics of the power spectrum distribution calculated from the training data. The number of electrodes was reduced to simplify the hardware setup and the computation processes, since our future goal for the DMB system is to provide a low-cost and portable home rehabilitation system. We used 4 criteria to choose the electrode. First, we only chose from electrodes placed on the contralateral side of the hand. Second, we chose an electrode located where positive ERD strength had been observed. In other words, we only chose an electrode that showed a larger power spectrum during the rest period than during the imagery period. Third, we chose the electrode that showed the highest discrimination rate among electrodes that satisfied the two conditions described above. We then formulated a classifier using linear discriminant analysis (LDA) and determined the discrimination rate using the leave-one-out algorithm. In case multiple channels showed the same discrimination rates, we selected a single channel among them that showed the highest mean ERD strength over the course of the training session. Finally, we choose a hand action of either ‘stop’ or ‘move’ for the online experiment depending on which showed higher a discrimination rate.

C. *Online BMI operation*

The online session used the condition decided from the procedures described in the previous section. The participant wore a glove-like assistive exoskeleton (Power Assist Hand: Team ATOM, Atsugi, Japan; Fig. 2). It is a pneumatic device used to change the hand shape to either grasped or open. The online session is almost the same as the offline data collection, except that proprioceptive feedback is given from the exoskeleton upon successful motor imagery. We calculated the power spectrum as we did in the offline analysis. If the EEG power at the rest and imagery periods satisfied the predetermined LDA criterion and were determined as ERD, the exoskeleton gave proprioceptive feedback with the visual feedback being displayed on the tablet screen. Users could receive immediate proprioceptive feedback via the exoskeleton to confirm whether they could properly imagine the hand action specified.

III. Effect of Synchronous / Asynchronous Proprioceptive Feedback on Motor Imagery Response

We used the DMB to investigate how the synchronous or asynchronous (delayed) feedback from visual and proprioceptive stimuli affects the ability to generate ERD response in stroke patients. The transition rates for successful operation of ERD-BMI and ERD strength were used to evaluate the accuracy of motor imagery.

A. Participants

Twenty-one chronic stroke patients with paralyzed hands (12 male, 9 female, 57.9±2.4 years old) participated in the experiment. The study was approved by the Institutional Review Board and all participants gave written informed consent prior to participation.

The participants were divided into two groups and were made to perform 12 online ERD-BMI operations in sequence. Participants in one group received synchronous proprioceptive and visual feedback (congruent feedback group, n = 11; Fig. 2) while the others received proprioceptive feedback 1s after the visual feedback (incongruent feedback group, n = 10). Proprioceptive feedback was given only when the patients successfully generated the ERD response. If the ERD strength failed to satisfy the threshold value to be determined as motor imagery by the classifier, they received visual feedback without proprioceptive feedback. Participants were asked about the congruency of visual and proprioceptive feedback at the end of the experiment. The number of trials was limited to 12 to prevent fatigue among the participants. The total time required for the experiment was less than 1 hour, including preparation, instructions, and training data collection.

B. Data analysis

The number of successful operations of the exoskeleton and ERD strength were compared between groups. We divided the 12 trials into 3 periods (first, middle, and last) to observe the transition of these parameters by repetitive use of the DMB. A successful operation rate was defined as the number of trials in which participants could operate the exoskeleton using their ERD response, divided by the number of total online trials in the period. The chance level of successful operation rate was also calculated using the same EEG data from online trials during the fixation period (Fig. 2). The statistical significance of the differences in successful operation rates between groups and among periods was investigated by t-test and repeated analysis of variance (ANOVA), respectively. Tukey's method for multiple comparisons between periods and groups of the corresponding period with Bonferroni correction further confirmed the time-dependent or group-specific difference in the performance of motor imagery. We considered P values < 0.05 to be statistically significant.

C. Results

The overall successful operation rates of the congruent and incongruent feedback groups were 56.8±5.2 and 40.0±3.5%, respectively. The chance levels were 36.4±4.5 and 35.4±4.5% in the congruent and incongruent feedback groups, respectively. Only participants in the congruent feedback group showed significantly higher successful operation rates compared to the chance level. Fig. 3 shows the transition of a successful operation rate. There was a significant difference

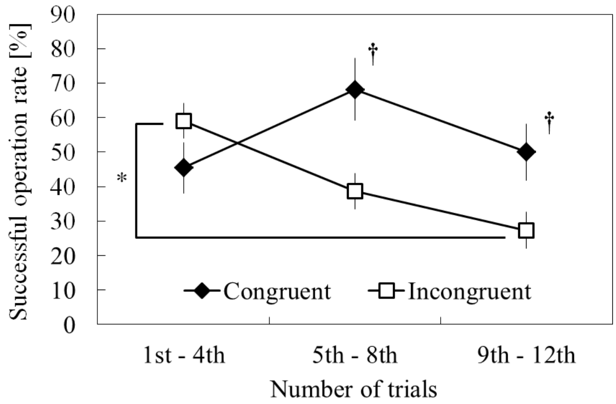

Fig. 3 Transition of successful operation rate through repetitive DMB trials.
Two-way repeated measure ANOVA and multiple comparisons.
†: Significant difference between congruent and incongruent groups. *: Significant difference between the first and last periods.

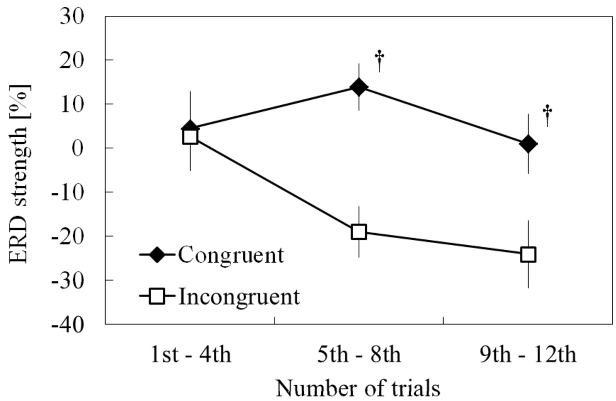

Fig. 4 Transition of ERD strength through repetitive DMB trials.
Two-way repeated measure ANOVA and multiple comparisons.
†: Significant difference between congruent and incongruent groups.

depending on the congruency of the multimodal feedback. Patients in the congruent feedback group maintained a successful operation rate with a slight increase over the course of the 12 trials, while those in the incongruent feedback group showed a continuous decrease in the successful operation rate. The successful operation rate of the participants in the incongruent feedback group was significantly decreased in the third period compared to the first period (significant interaction between period and group; two-way repeated measures ANOVA, $F(2,40) = 5.85$, $P = 0.06$, followed by multiple comparisons with Bonferroni correction). The successful operation rates in the second and the third periods were significantly lower in the incongruent feedback group compared to those in the congruent feedback group.

The ERD strength averaged across all trials in the congruent and incongruent feedback groups was 5.6±4.2 and -13.5±9.9%, respectively. Participants in the congruent feedback group achieved a statistically larger overall ERD strength than those in incongruent feedback group.

Fig. 4 shows the transition in ERD strengths for both groups. The transition of ERD strengths corresponded to successful operation rates in experimental conditions. Although the ERD strengths of both groups are comparable in the first period, those in the incongruent feedback group showed a gradual decrease as trials progressed to reach a statistical significance between groups in the second and third period.

The post-experiment questionnaire indicated that only 3 out of 10 participants in the incongruent feedback group recognized the delay between visual and proprioceptive feedback.

D. Discussion

Using our developed ERD-BMI system, we investigated the importance of multimodal feedback timing corresponding to successful motor imagery in stroke patients. Our results show that the increased successful operation rate in BMI and ERD strength in the congruent group over the incongruent group confirmed the positive effect of congruent proprioceptive feedback on the ERD-BMI training that was previously reported in healthy participants [2]. The transitions of successful operation rate and ERD strength indicate that delayed feedback affects the ability of motor imagery in stroke patients. A previous study with healthy young adults showed that 1 s of delay between visual and somatosensory stimuli was almost completely perceptible [20]. Interestingly, among the 10 stroke patients enrolled in the incongruent feedback group, only 3 of them could notice the delay, but their overall successful operation rate and ERD strength were severely affected by incongruent multimodal feedback. It is likely that the damage in the stroke-affected brain deteriorates the function to integrate and interpret motor intent and sensory input. Our results for continuously decreasing ERD strengths through trials in the incongruent feedback group clearly indicate that the lower-functioning integrative centers in patients are more vulnerable to timing-incongruent multimodal feedback. These results suggest that stroke recovery might be inhibited if visual and proprioceptive feedbacks are timing-incongruent in ERD-BMI rehabilitation because ERD strength is a measurement of the functional recovery of the motor cortex in post-stroke patients [21]. On the other hand, ERD strength showed an increase in patients with BMI operation from the first to the second third of the trials when they received timing-congruent feedback which was maintained until the completion of the all of the trials. Therefore, the congruency in the timing of multimodal feedback may play an important role in the success of the ERD-BMI rehabilitation of the paralyzed hands in stroke patients. The decrease observed in successful operation rate and ERD strength from the middle to the last periods found in both groups may be due to the effect of fatigue through repetitive trials, however further study is required to determine the effect of long-term training with the DMB. Additionally, a comparison of the proposed system with the one without proprioceptive feedback (visual feedback only) would be beneficial to determine the contribution of multimodal feedback.

IV. CASE STUDY OF COMBINED RTMS AND DMB IN HAND MOTOR REHABILITATION OF A CHRONIC STROKE PATIENT

This section introduces a clinical case study in which we used the DMB on a hospital inpatient involved in an intensive rehabilitation program for hand motor function.

E. Participant

A 50 year-old female chronic stroke patient with paralysis in her left hand after right-middle cerebral artery occlusion participated in the clinical trial. The Brunnstrom recovery stage of her upper limb and hand function was IV (the state of spasticity slightly reduced) on admission. Her complaint in ADL was that a spasm in her thumb after a pinching movement prevented her from folding laundry. The study was approved by the Institutional Review Board and the participant gave her written informed consent.

F. Intervention and functional evaluation

A single rehabilitation session consisted of three consecutive sub-sessions of low-frequency repetitive transcranial magnetic stimulation (LF-rTMS), ERD-BMI using DMB, and occupational therapy. LF-rTMS was applied to the primary motor cortex of the unaffected hemisphere to decrease the corticospinal excitability in the unaffected hand motor area. There is a correlation between motor function improvement and corticospinal excitability changes in the affected hemisphere and reducing corticospinal excitability in the unaffected hemisphere has been reported to induce its recovery in the affected side [22]. The participant received a single train of 1300 rTMS stimuli to the unaffected hemisphere over the hand primary motor cortex, with an intensity of 90% resting motor threshold (RMT) at a frequency of 1 Hz. Following the LF-rTMS, the participant engaged in 12 trials of repetitive ERD-BMI training. Finally, the participant received occupational therapy from a therapist for 60 minutes. Twenty-two sessions were conducted over 14 days.

The motor function of the participant was assessed by the Modified Ashworth Scale (MAS) of the thumb metacarpophalangeal (MP) joint extension at rest and after maximal voluntary pinching, and the execution time and functional ability scale (FAS) of the Wolf Motor Function Test (WMFT). A neurophysiological assessment was conducted by measuring motor evoked potential (MEP), strength of ERD in a separate EEG measurement besides DMB, and by performing an F-wave evaluation. A single TMS stimulus was given to the primary motor area of the unaffected hemisphere with an intensity of 110% RMT 10 times to obtain MEP from the first dorsal interosseous. An EEG measurement was conducted with an alternating 10 s of rest and hand motor imagery 30 times to determine motor-imagery induced ERD strength. Additionally, spinal cord excitability of the affected hand was evaluated from the primary (M-wave) and secondary (F-wave) amplitudes of the thenar muscle response with electrical stimulation of the median nerve. The stimulation intensity was set to 120% of maximal M-wave stimulation at thenar muscle of the unaffected side. The participant received 16 doses of median nerve stimulation at a duration of 0.2 ms at 1 Hz during rest and hand motor imagery. The amplitude ratio (F/M) during motor imagery was determined as the relative value to that during rest state.

G. Results

The motor function and neurophysiological indices were improved through the intensive rehabilitation as shown in Table 1 and Fig. 5 shows the improved voluntary thumb and finger extension ability pre- and post- intervention. The spasmus in the thumb became well controlled after the intervention, which allowed the patient to use both hands to fold laundry.

H. Discussion

Decreased MEP amplitude and ERD strength in the unaffected hemisphere indicates the suppression of excessive activity of the primary motor area of the unaffected hemisphere, which is beneficial for functional recovery of the primary motor cortex of the affected hemisphere [22]. On the other hand, the ERD strength in the affected hemisphere was increased, which corresponds to improved ability for motor imagery to generate motor commands to the peripheral muscles [23]. A decrease in F/M amplitude ratio indicates the change in the proportion of larger and smaller motor units [24], suggesting that greater incorporation of smaller motor units enables finer control of hand muscles. These neurophysiological improvements are considered to achieve the motor functional recovery in MAS and WMFT. Although this is a single case study without any control conditions or patient groups, the results suggest that the combined suppression of the unaffected motor cortex by rTMS and the encouraged use of the affected motor cortex by ERD-BMI, have potential to reorganize the motor pathway for functional recovery by suppressing unnecessary spinal excitability. Further case studies comparing therapy outcomes between rTMS-only and combined rTMS and DMB therapy could specify the contribution of DMB to the functional recovery.

TABLE I
RESULT OF FUNCTIONAL AND NEUROPHYSIOLOGICAL EVALUATION

Evaluation items	Pre-intervention	Post-intervention
MAS of the thumb MP joint extension at rest (0: no increase in tone, 4: rigid in flexion or extension)	1	0
MAS of the thumb MP joint extension after maximal voluntary pinching	2	1+
WMFT execution time	44s of decrease at Post intervention	
WMFT FAS	9 points increase at Post intervention	
MEP amplitude in unaffected hemisphere [μV]	148.4 ± 38.5	96.3 ± 22.0
ERD strength in affected hemisphere [%]	3.15	11.9
ERD strength in unaffected hemisphere [%]	8.83	4.96
Relative F/M amplitude ratio	1.04	0.90

Fig. 5 Improvement in extension ability in the thumb and finger joints after 22 times of combined rTMS and DMB therapy. Photographs show the voluntary maximal hand extension after maximal voluntary grasping at pre- (left) and post- (right) intervention.

V. CONCLUSIONS

Neurorehabilitation, a combined field of robotics, signal processing, and neuroscience, has emerged as a promising clinical application to maximize the functional recovery of stroke patients with hemiplegia. Our newly developed DMB system encourages motor imagery in the affected hemisphere via an action observation paradigm and provides timing-congruent proprioceptive feedback to accelerate reorganization of the sensory-motor pathway. Further investigation would evaluate the feasibility of our system in patients with varied severities of paralysis. Another direction is to provide a cost-effective and automated prototype of DMB so that patients could train themselves at home, since the time engaged in rehabilitation plays a key role in the functional recovery.

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