Research Article

Hemiparetic Stroke Rehabilitation Using Avatar and Electrical Stimulation Based on Non-invasive Brain Computer Interface

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Abstract

Brain computer interfaces (BCIs) have been employed in rehabilitation training for post-stroke patients. Patients in the chronic stage, and/or with severe paresis, are particularly challenging for conventional rehabilitation. We present results from two such patients who participated in BCI training with first-person avatar feedback. Five assessments were conducted to assess any behavioural changes after the intervention, including the upper extremity Fugl-Meyer assessment (UE-FMA) and 9 hole-peg test (9HPT). Patient 1 (P1) increased his UE-FMA score from 25 to 46 points after the intervention. He could not perform the 9HPT in the first session. After the 18th session, he was able to perform the 9HPT and reduced the time from 10 min 22 sec to 2 min 53 sec. Patient 2 (P2) increased her UE-FMA from 17 to 28 points after the intervention. She could not perform the 9HPT throughout the training session. However, she managed to complete the test in 17 min 17 sec during the post-assessment session. These results show that the feasibility of this BCI approach with chronic patients with severe paresis, and further support the growing consensus that these types of tools might develop into a new paradigm for rehabilitation tool for stroke patients. However, the results are from only two chronic stroke patients. This approach should be further validated in broader randomized controlled studies involving more patients.

Introduction

Each year, millions of people worldwide have a stroke, which causes various degrees of upper limb paresis in about a third of these patients [1]. This can severely limit their freedom to perform daily activities independently, and leads to tremendous personal and societal costs including reduced dignity, freedom to work, and ongoing dependence on carers and specialized devices. Rehabilitation approaches such as constrained induced movement therapy (CIMT) encourages patients to use their affected limb more often, and has led to both physiological changes in sensorimotor cortices and behavioral improvement [2]. However, this therapy only benefits patients who retain some residual movement in the affected limb. Alternatively, passive movement therapies are available for these patients. For example, robotic training has been practiced in the clinical environment for repetitive motor training [3].

The broader problem with existing therapies is that they do not monitor the patient's engagement in the rehabilitation therapy process. Some patients may be able to use electromyography (EMG) or other means to trigger robotic devices and show therapists that they are actively performing the task as expected [4]. If patients have little or no residual movement, therapists may have no objective means to confirm that patients are complying with the task. Synchronizing the patient's motor execution (or motor imagery) with sensory feedback is widely considered crucial in rehabilitation therapy. The inability to detect movement imagery in conventional rehabilitation therapy may explain why robotic training and other rehabilitation therapy approaches for persons with severe paresis are often ineffective. Indeed, they may yield little or no benefit over traditional therapies, including passive functional electrical stimulation FES therapy [5,6].

Motor imagery based brain-computer interfaces (BCIs) provide a way to monitor patients' motor imagery, even if they cannot move. Thus, they can provide a real-time, objective measure of each patient's task engagement, which can be used to assess compliance and trigger devices such as an FES or visual feedback on a monitor. The efficacy of BCIs has been shown in multiple studies implementing exoskeletons, robots, monitor feedback, and/or FES systems that induce passive movement of their affected limbs [7-11].

Ramos-Murguialday and his colleagues showed that a group with contingent online BCI feedback using hand orthoses and an arm robot had significantly less motor impairment after the intervention than a group with random feedback [8]. Their BCI training was followed by physiotherapy. Recently, another BCI study showed the potential of motor imagery rehab in subacute patients with severe motor impairment [12]. The feedback from virtual hand movement was provided only after successful motor imagery trials. The BCI group showed better functional outcome than a group with conventional therapy group [12].

In this paper, two chronic stroke patients with severe upper limb paresis used a motor imagery based BCI to control an FES and non-immersive virtual upper limb (avatar) feedback by imagining left or right wrist dorsiflexion as instructed by a therapist. In the previous BCI studies, the EEG acquired during the trials was classified into idle state or activated state [7-11], but we classified the signals into left or right motor activity. We trained the patients with BCI feedback alone without any other physiotherapy. To my knowledge, this is a unique system based on non-invasive motor imagery BCI controlling avatar and FES for stroke rehabilitation. Our main goal in this study was to

explore any improvement in motor function of two chronic stroke patients, but we also assessed changes in their BCI performances.

Patients and Methods

Study design

Patients participated in 25 60-minute sessions of BCI training over three months, with about two sessions per week. Behavioural assessments were performed two days before the first training session and two days after the last training session. Informed consent was obtained from both participants. The therapy was conducted by a therapist with appropriate licensing in Austria (author MZ). All interaction with patients, including the language settings used, occurred in German, which is the native language of the patients and the therapist.

Patients

Two patients joined this study: one male with right limb paresis and one female patient with left limb paresis. Their strokes were in the chronic phase when they started the training. They did not receive any other therapy during the intervention and fulfilled the following inclusion criteria: (1) ability to understand written and spoken instructions from therapists; (2) hemiparesis; (3) time since stroke of at least 4 days; (4) stable neurological status other than stroke; (5) ability to participate in the study for 3 month; (6) no pregnancy; (7) no implanted medical devices such as pacemakers; (8) no implanted metallic fragments in the upper extremities; (9) no cerebellar lesion; (10) no severe hemi-neglect; (11) no epilepsy; (12) no fractures or lesions in the upper extremities; (13) no severe lung diseases or liver disease; (14) no severe pusher syndrome; (15) ability to maintain a seated position for one hour; (16) no sensory disorder feeling pain or unsuitably reacting to sensory stimuli; (17) no peripheral nervous diseases affecting the upper limbs (brachial plexus pals and cervical radicular syndromes).

Patients with severe spasticity were not excluded, because FES still can provide the sensory feedback from contracting muscle spindles, tendons, and other skin receptors.

	Age (years)	Gender	Paretic side	Time since stroke (months)
P1	53	male	right	11
P2	54	female	left	360

Table 1: Patient information.

BCI methods

Each session contained four runs and lasted 60 minutes in total, including preparation and clean-up. Sessions were terminated if patients were not able to continue due to their illness or fatigue. 16 EEG electrodes (g.LADYbird, g.tec medical engineering GmbH) were placed over the sensorimotor area of the cortex according to international 10/10 system (extended 10/20 system): FC5, FC1, FCz, FC2, FC6, C5 C3, C1, Cz, C2, C4, C6, Cp5, Cp1, Cp2, Cp6. A reference electrode was located on the right earlobe and a ground electrode was at FPz.

Throughout the procedure, patients sat in a comfortable chair and placed their forearms on a Table 1. Before recording, the cap was mounted on the patient's head, and FES parameters were adjusted to find the individual current amplitude to induce wrist dorsiflexion in each session without causing discomfort. Two FES electrodes were placed on the wrist extensor muscles of the left and right forearms, respectively. The FES stimulation was set to a frequency of 50 Hz with a pulse width of 300 μs. The therapist increased the intensity of stimulation until smooth movement of wrist was observed in patients with mild and moderate impairment, or until muscle contraction was observed in the target muscle of their paretic side for patients with severe impairment (Figures 1-5).
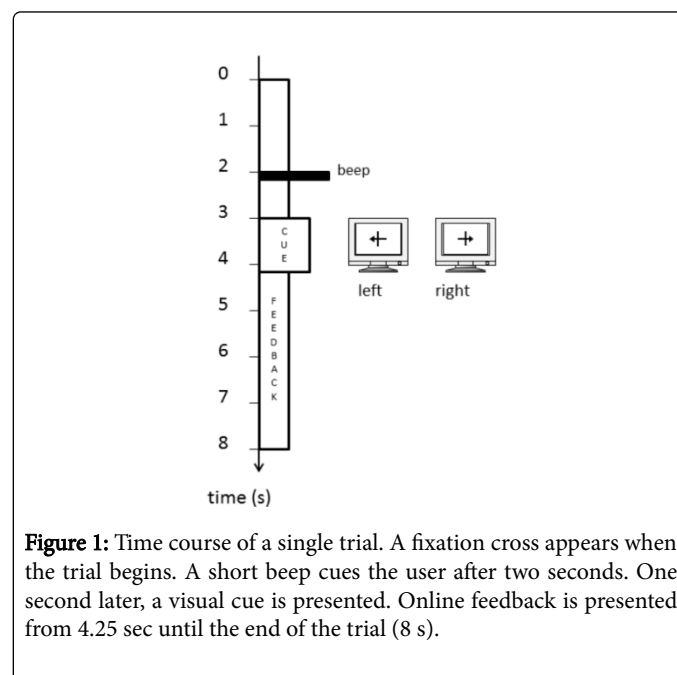

Figure 1: Time course of a single trial. A fixation cross appears when the trial begins. A short beep cues the user after two seconds. One second later, a visual cue is presented. Online feedback is presented from 4.25 sec until the end of the trial (8 s).

Patients were asked to imagine left or right wrist dorsiflexion according to visual and auditory cues from the BCI system. The sequence of motor imagery tasks was specified in pseudo random order with randomized inter-trial intervals. A beep was played to start each trial. An animated green arrow and spotlight to either the left or right hand visually instructed the patient to imagine left or right-hand movement. The patient also received an auditory instruction, which was a recorded voice that said "left" or "right" in German. When the system classified the correct side of movement from the EEG during feedback phase (3.5~8 sec), the FES and avatar were activated. This decision was updated every 200 ms.

Assessment

One therapist measured all the assessments before and after the intervention. 9HPT was conducted during the training sessions as well to observe their behavioural progress.

Primary behavioural outcome measure

The FMA is a common way for therapists to evaluate patients' motor impairments, with excellent interrater reliability [13,14]. We used the FMA of upper extremity (maximal score=66 points) as a primary behavioural outcome measure because this BCI training focuses on the upper limbs.
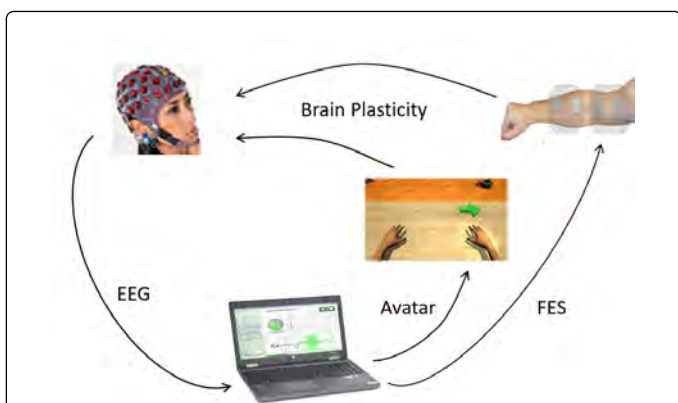
Figure 2: Brain computer interface system. A complete BCI system (recoveriX, g.tec medical engineering GmbH, Austria) was used. EEG signals were transmitted to an biosignal amplifier (g.USBamp, g.tec medical engineering GmbH, Austria). Common spatial pattern (CSP) [18] was applied to transform the preprocessed data to a new matrix with minimal variance of one class and maximal variance of the other class. The transformed matrix reflects the specific activation patterns of the data during motor imagery of left or right hand in this study. Linear discriminant analysis (LDA) classifier was used to control FES and Avatar. (Please refer to the Materials and Methods of Cho et al. for more detail [19]. After each run, offline classification accuracy is done *via* cross validation. The accuracy is calculated for all movements in the testing pool within a time window of 1.5 seconds after the attention beep until the end of the trial, in steps of half a second. For each step and each trial, the classification result is either 100% or 0%. The accuracy of all trials of the test pool is then averaged for each single step, resulting in accuracy levels ranging between 0% and 100%.

Secondary behavioral outcome measures

The 9-hole peg test (9HPT) measures the time to finish a given task to test finger dexterity. The Barthel Index (BI) is a questionnaire to measure the ability to care for him/herself. Modified Ashworth Scales examine spasticity, with a lower score reflecting lower spasticity in the paretic limb.

The wrist (MASWrist) and hand (MASHand) was tested for this assessment. Fahn's tremor rating scale (FTRS) scores the tremor degree by counting the number of crossing the border of spiral image on paper with a pen. A lower score in FTRS means less tremor.

Results

Behavioural Outcome Measures

P1: FMATotal increased remarkably-from 25 to 46 points. Both FMAWrist and FMAHand increased from 0 to 6 points and from 3 to 11 points respectively as well as FMAUE from 22 to 27 points. The BI improved from 90 to 95 points. The MAS showed reduced spasticity in the paretic wrist (from 2 to 1) and hand (from 1.5 to 1). FTRS also reduced from 4 to 3 points. It was not possible to conduct 9HPT due to the level of impairment when the therapy started. After the 18th session, P1 was able to participate in 9HPT. The elapsed time required decreased from 10 min 22 sec to 2 min 53 sec in the paretic side, while the completion time for the non-paretic side was fairly stable.
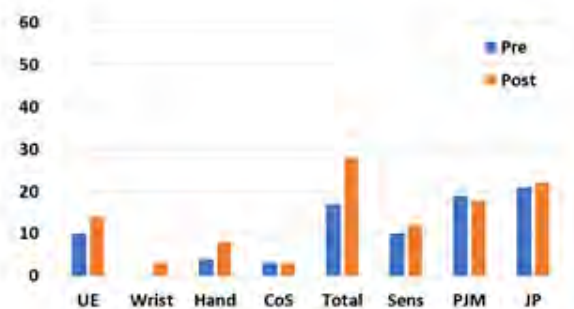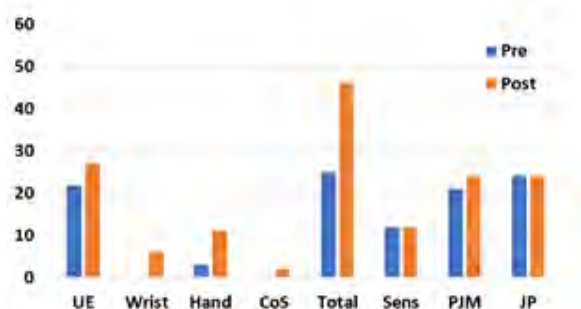

Figure 3: FMA scores of P1 and P2. Upper extremity FMA of P1 and P2 with subscores of upper extremity (FMAUE), wrist (FMAWrist), hand (FMAHand), coordination and speed (FMACoS), sensation (FMASens), passive joint motion (FMAPJM), and joint pain (FMAJP). The FMAtotal is the sum of subscales from FMAUE, FMAWrist, FMAHand, and FMACoS. The blue and orange bars show pre-measurement and post-measurement respectively.

P2: The FMATotal increased from 17 to 28 due to higher scores in FMAUE (10 to 14), FMAWrist (0 to 3), and FMAHand (4 to 8) after the intervention. The FMASens and FMAJP scores increased by 1 and 2, respectively. However, FMAPJM decreased by 1 point. MASWrist decreased from 3.5 to 1.5 and MASFingers did not change across sessions. Despire the higher FMA and reduced MASWrist, no changes in BI were observed, and FTRS increased from 3 to 4 points.
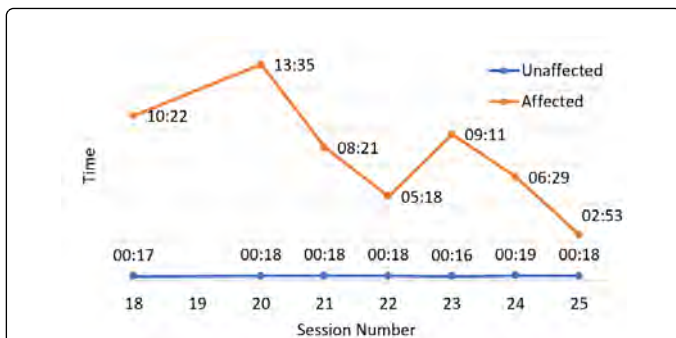
Figure 4: 9HPT of P1. It was not possible for P1 to conduct the 9HPT until the 17th session. He first completed the test after the 18th session and reduced the time from 10 min 22 sec to 2 min 53 sec. The blue and orange lines show the results of unaffected and affected sides, respectively. (*P2 could not perform the test throughout the training session due to the severe impairment).

BCI performance

The MCA of P1 was 66% in the very first session. He quickly improved, reaching 100% MCA in the 7th session. He then maintained high accuracy (94% mean MCA from 7th to 25th sessions). His accuracy was lower in the 14th and 20th sessions, which he reported was due to inattention and fatigue. On the other hand, the MCA of P2 was relatively low, and was fairly consistent (71% mean MCA over sessions).
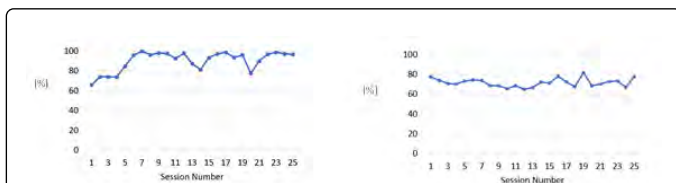

Figure 5: Maximum classification accuracy of P1 and P2.

Discussion

Five assessments were performed to evaluate the sensorimotor recovery after the intervention with different widely established tests to measure behavioural changes. The FMATotal showed motor improvements in both patients. The score includes the UE, wrist, hand, and coordination and speed, so it reflects the overall motor improvement in upper extremities. Patients were instructed to imagine wrist dorsiflexion, while sensory feedback was provided only when the EEG indicated that the patient was imagining the task properly. The higher UE score can be explained by implicit motor learning during the training.

The 9HPT was the most responsive among these five assessments. The time to complete the tasks of P1 in session 1 dramatically reduced in their paretic side after the intervention. Questions can rise up about the number and it may come from learning mental strategies instead of motor recovery. When we compare the overall time of healthy side, it does not support that the shortened time is from learned mental strategies. Our primary measure, FMA indicated that P1 improved in

motor recovery. However, P1 could not perform the 9HPT until the 18th session, because of his impairment. It has high sensitivity in functional improvement in upper limbs and is more applicable for the patients with moderate and mild impairment. Lin and his colleagues showed that the 9HPT is suitable to find improvements over time, but the Box and Block Test is more appropriate to test hand dexterity [15]. The high responsiveness of 9HPT may come from three-month training period.

The FMATotal results were supported by other secondary measures. Both patients showed lower score in either MASWrist or MASHand, which reflects reduced spasticity after the training. Reduced spasticity is a key element in regaining motor control after paralysis. The FTRS of P1 also decreased, implying that P1 could move his hand with less tremor. However, the FTRS of P2 increased by one point, because the drawing was done with the assistance of healthy hand in pre-assessment and without it in post-assessment.

These functional improvements are especially noteworthy in that they occurred in chronic patients with severe paresis. P2's stroke occurred 30 years ago, and she showed clear motor recovery. She had participated in physiotherapy several times with many different practitioners and methods, but she had not observed any improvement until her experience with BCI training. The time after stroke onset may be less crucial in motor improvement with BCI rehabilitation. Moss and Nicholas also showed that the time after stroke onset was not relevant to therapy for aphasia patients [16]. However, it still needs systematic studies to show the importance of the time after stroke onset in BCI rehabilitation training.

BCI classification accuracy may be another important measure. P1 learned how to use BCI and reached an accuracy of 100% multiple times. P1 had greater improvements in behavioural scales, and his classification accuracy was higher than P2's, which means that he received more concurrent sensory feedback with motor imagery task than P2. On the other hand, P2 did improve despite lower accuracy, and other work has shown that functional improvements are possible despite relatively low BCI accuracy [17]. Thus, high BCI accuracy could lead to greater functional improvement, but may not be required. The relationship between BCI accuracy and functional improvement is an interesting topic for future research.

Study limitations

The major study limitation was a small number of sample size (n=2). Stroke can occur at any age, and affect any area of brain. The resulting heterogeneity among patients creates challenges in predicting outcomes of BCI rehabilitation treatment, as well as deciding which patients would benefit most and how to tailor therapy to each patient. Far more research is needed to identify the optimal parameters for each patient and explore other ways to help them. Even though this study has shown that this approach can lead to substantial improvement in chronic patients with severe paresis, these are results from only two patients.

Future Research Direction

Most importantly, broader clinical validation is needed, with enough participants for appropriate statistical evaluation. Randomized controlled studies are required to test a hypothesis that this BCI approach using avatar and FES promotes more functional recovery than other traditional therapies.

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