32nd Annual International Conference of the IEEE EMBS
Buenos Aires, Argentina, August 31 - September 4, 2010

# Post-Acute Stroke Patients Use Brain-Computer Interface to Activate Electrical Stimulation

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***Abstract* — Through certain mental actions, our electroencephalogram (EEG) can be regulated to operate a brain-computer interface (BCI), which translates the EEG patterns into commands that can be used to operate devices such as prostheses. This allows paralyzed persons to gain direct brain control of the paretic limb, which could open up many possibilities for rehabilitative and assistive applications. When using a BCI neuroprosthesis in stroke, one question that has surfaced is whether stroke patients are able to produce a sufficient change in EEG that can be used as a control signal to operate a prosthesis.**

**The aim of this paper is to determine if post-acute (<3 months) stroke patients are able to use an electroencephalogram (EEG)-based BCI to trigger neuromuscular electrical stimulation (NMES)-assisted extension of the wrist and fingers.**

**EEG was recorded while subjects performed motor imagery of their paretic limb, and then analyzed to determine the optimal frequency range within the mu-rhythm that showed the greatest attenuation. With the help of visual feedback, subjects then trained to regulate their mu-rhythm EEG to operate the BCI to trigger NMES on their wrist extensor muscles.**

**9 post-acute (<3 months) stroke patients, aged 58.2 ± 9.3 yrs, participated in this study. 4 out of 6 subjects who completed the trial are able to use the BCI to trigger NMES on their paretic wrist extensor muscles.**

**This study presents findings that movement intention, as characterized by the attenuation of *mu*-rhythm EEG, is detectable in post-acute stroke patients, and that this signal is can be used as a control signal for the patients to operate a BCI to trigger NMES.**

## I. Introduction

Upper limb weakness and loss of function as a result of stroke is a significant problem amongst survivors – up to an estimated 66% [1,2] of hemiplegic stroke patients will have a functionally useless arm. To combat the debilitating effects of paralysis, technology has been employed on many fronts to improve stroke rehabilitation. New methods are being developed to engage the stroke survivor in intense, task-specific and motivating exercises. One such concept that opens up possibilities for rehabilitative or assistive applications is direct brain control of the paretic arm, with the use of brain-computer interfaces (BCI) to operate either robotics or neuromuscular electrical stimulation (NMES). The premise is that such a system would activate both the efferent and afferent neural pathways of the nervous system, and lead to greater neuroplasticity and thus functional recovery.

The use of an electroencephalogram (EEG)-based BCI is particularly attractive in this application – it is non-invasive, and equipment is not bulky and relatively inexpensive. Among the various mental strategies that induce EEG changes, we are interested in the EEG changes brought about by motor imagery, as this is the closest proxy to actual limb movement that we hope to rehabilitate. Motor imagery is characterized by attenuation of the mu-rhythm (8-12 Hz) when one thinks of moving, a phenomenon termed as event-related desynchronization [3]. In this study, we use this phenomenon to control an on-screen cursor to trigger NMES on the wrist extensor muscles.

Using a brain-computer interface (BCI), however, is not easy; both man and machine must undergo a certain amount of training in order to use it, and high levels of concentration must be maintained during its use. Thus, when using a BCI in stroke, one question that arises is whether stroke patients are able to produce a sufficient change in EEG for it to be used as a control signal.

The aim of this study was to evaluate whether acute stroke patients (<3 months post-stroke) are able to control a BCI to trigger neuromuscular electrical stimulation (NMES)-assisted extension of the wrist and fingers, which are the essential pre-requisites for useful hand function.

As most motor recovery occurs within 6 months of stroke onset, interventions to facilitate recovery, including BCI-based therapy, should ideally occur during this time frame. However, there have been very few studies examining the use of BCI in patients less than 6 months post stroke onset, and hence little is known about their ability to operate a BCI-NMES neuroprosthesis. In a study by Buch et al, it was demonstrated that 6 out of 8 chronic stroke patients with hand plegia were able to learn to operate a binary magnetoencephalography (MEG)-based BCI after 13-22 sessions, to voluntarily open and close a prosthesis attached to their paralysed hand [4]. In another study, 5 chronic (>6 months) stroke patients with severe upper limb paresis

Manuscript received March 16, 2010. This work was supported in part by Nanyang Technological University, Institute for Infocomm Research, and Tan Tock Seng Hospital.

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managed to regulate their EEG to gain control of a binary BCI after 9 training sessions [5]. This study therefore sheds light on post-acute stroke patients' use of an EEG-based BCI.

## II. METHODS

### A. Participants in the Study

This was a pilot study of patients with a first clinical stroke admitted to a rehabilitation centre. Patients recruited for this study were between 21-80 years old, had a stroke diagnosed by a CT and/or MRI brain scan, were within 3 months post-stroke, and had a Medical Research Council (MRC) power grading of less than 4 on their paretic wrist. Patients with a history of seizures or epilepsy, neurosurgical operations, presence of a pacemaker, or with significant cognitive and/or language deficits were excluded, and so were those with muscular contractures of more than 3 on the Modified Ashworth Scale.

Informed consent was sought from all patients, and the study was approved by the Institutional Review Board of Tan Tock Seng Hospital.

### B. BCI Protocol

Of particular interest in this study is the free-running EEG signal in the *mu* (8-14 Hz) band, over the motor cortex of the brain. This corresponds to electrode positions FC3, FC4, C3, C4, CP3, and CP4 of the international 10/20 montage for EEG electrodes [6]. It has been shown that people can learn to regulate their *mu*-rhythms, and that the amplitude of the *mu*-rhythm is largest when the subject is not moving or not imagining any movement, and attenuates when the subject is moving or imagines movement [7].

After being band-pass filtered to within 8-25 Hz with a 4th order Butterworth filter, EEG was then decomposed, using the Bandlimited Multiple Fourier Linear Combiner [8], into frequency intervals of 1 Hz over the range of the rhythm such that the amplitude of each frequency could be determined. Figure 1 shows the average amplitude of each frequency of the *mu*-rhythm, over the contra-lesional hemisphere, over a 5-second interval, during which the subject did nothing (resting) or performed hand movement. The frequency range from 8-12 Hz exhibited the greatest attenuation. The band that exhibited the greatest attenuation during motor imagery was used to control an on-screen cursor, which in turn was used to control NMES on the paretic limb [9,10].

Subjects who were unable to move their paretic hand were instructed to imagine the movement, as it has been shown that actual and imagined movements produced similar EEG patterns [11].

EEG acquisition was mono-polar with the right earlobe as the common reference point, and sampled at 250 Hz. Conducting gel was used between the electrodes and scalp surface to reduce impedances to below 5 kΩ.

### C. Training to Use BCI

Upon identification of the optimal band and movement that causes a significant change in EEG, the patient learnt to regulate his/her EEG in order to control an on-screen cursor. The change in EEG was mapped onto a one-dimensional position of the cursor. Typically, subjects used hand grasping and wrist flexion/extension movements to elicit motor imagery. Under this operant conditioning approach, subjects had to experiment with various hand movements in order to produce a repeatable change in EEG to move the cursor, which acts as feedback for the learning process.

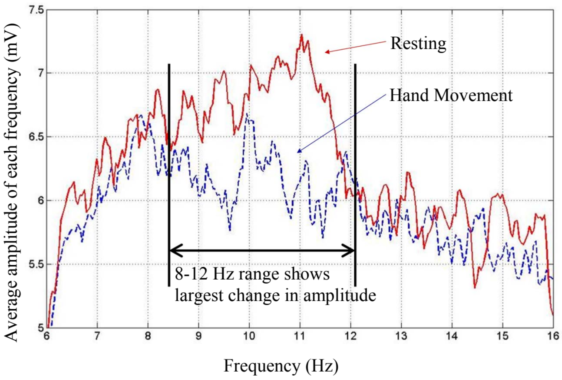


Fig. 1. Average amplitude of each frequency of the *mu*-rhythm over a 5-second interval, while the subject rested or performed hand movement. The 8-12 Hz band displayed a noticeable attenuation of the signal during hand movement.

Subjects were also instructed not to clench facial muscles, through eye or eyebrow movements or biting during the training. Such actions would introduce EMG artefacts, which are of higher frequency and amplitude, and thus undesirable in EEG analysis. Whenever EMG artefacts were observed, that segment of the training was ignored.

As a high level of concentration was needed to elicit the necessary changes in EEG, each session generally lasted no longer than 1 hour because of the onset of mental fatigue, which diminished the effectiveness of training.

Once the subject was able to operate the BCI, NMES was introduced. The paretic arm was placed such that the wrist could flex/extend in a gravity-eliminated plane, and the forearm was midway between supination and pronation. When the cursor was moved horizontally across to the end of the screen, electrical stimulation of the extensor muscles was triggered to induce wrist extension.

### D. Neuromuscular Electrical Stimulation (NMES)

NMES of the wrist and finger extensors was delivered through the Compex Motion electrical stimulator [12] via a pair of 25 $cm^2$ self-adhesive electrodes. One electrode was placed proximally over the forearm below the elbow, and the other was placed distally on the forearm (positioned for optimally balanced joint movement). Stimulation frequency and pulse width were held constant at 25 Hz and 250 µs respectively, while current amplitude was adjusted for individual subjects. Joint angle was acquired by a Biopac TSD130B goniometer and used as feedback to determine completion of the NMES-assisted movement, which corresponds to the maximum passive wrist extension for each individual. Whenever NMES was triggered, the BCI was paused until the NMES-assisted movement was completed. Electrical stimulation was stopped when the wrist reached full extension.

## III. Results

9 subjects with a stroke, 7 male and 2 female, aged 58.2 ± 9.3 years participated in this study. The demographic and clinical characteristics of the patients are shown in Table 1. The subjects were studied at a mean of 31.4 days post-stroke (range 8 – 66 days). The motor power of wrist extension was less than grade 3 in all but 1 subject. 3 subjects had complete plegia of the affected upper extremity (subject 5, 7, 8). With regards to site of stroke, 2 were predominantly cortical, 5 subcortical and 2 brainstem.

3 subjects did not complete BCI training for the following reasons: one decided to withdraw from the study after 1 session (subject 4), as he was concerned that BCI training may affect his health, another was discharged home prematurely after 1 session and chose not to continue (subject 6) and the last subject could not participate in BCI training because of short attention span and left-sided neglect (subject 8).

Of the remaining 6 subjects, 4 (subject 2, 3, 5 and 9) were successful in controlling the BCI. Subject 2 had a cortical stroke while the other 3 had subcortical strokes. All 4 subjects took less than 2 hours to learn to use the BCI to activate NMES of the wrist and finger extensors. The average duration to trigger NMES was 42 seconds.

Of the two subjects who could not use the BCI after 5 sessions of training, one (subject 7) did not have a sufficient change in EEG that could be used to control the BCI. While the other patient (subject 1) had a noticeable change in EEG, he was unable to regulate it in order to control the BCI correctly.

Apart from subject 4 who was concerned that BCI training may affect his health, no adverse events were reported in the other 8 subjects.

TABLE I
Demographic and Clinical Characteristic of Subjects (N=9)

| No | Age/ Sex | Days After Stroke | Nature of Stroke | Location of Stroke | Affected Hand / MRC Score | Used BCI? |
|---|---|---|---|---|---|---|
| 1 | 61/M | 56 | Infarct | Pons | Left/2 | N |
| 2 | 54/M | 66 | Infarct | Frontoparietal Lobe | Left/3 | Y |
| 3 | 48/M | 12 | Hemo-rrhage | Basal Ganglia | Left/4 | Y |
| 4 | 64/M | 10 | Infarct | Corona Radiata | Left/1 | N |
| 5 | 73/M | 34 | Infarct | Corona Radiata & Lentiform Nucleus | Left/0 | Y |
| 6 | 48/F | 12 | Infarct | Pons | Left/4 | N |
| 7 | 69/F | 26 | Infarct | Corona Radiata & Lentiform Nucleus | Right/0 | N |
| 8 | 56/M | 8 | Infarct | Frontoparietal Lobe & Corona Radiata | Left/0 | N |
| 9 | 51/M | 59 | Infarct | Frontoparietal Lobe & Corona Radiata | Right/2 | Y |

MRC: Medical Research Council motor power score

## IV. Discussion

In this study, we ask the question of whether patients with an acute to subacute stroke could control a BCI to activate NMES of the wrist/finger extensors. The reason for choosing NMES of the wrist/finger extensors was because NMES has been demonstrated in previous studies to facilitate upper limb recovery in stroke [13,14,15] and active wrist/finger extension are pre-requisites for useful hand function. The study findings indicate that movement intention, as characterized by the attenuation of mu-rhythm EEG, is detectable in 4 of 9 subjects (44.4%) at an average of 31.4 days after stroke onset, and they could use this method to operate a BCI to trigger NMES on the paretic wrist.

Encouraging is the finding that the 4 successful subjects managed to learn and use the BCI with only 2 sessions. It has been estimated that about 1 in 5 persons are 'BCI illiterate' because their motor-related mu-rhythms do not show sufficient variation to be used as a control signal [16]. As the sample size of this study was small, no conclusion can be made on the rate of BCI literacy among post-acute stroke patients, and neither are we able to comment on meaningful differences in clinical or stroke characteristics between those who succeeded and those who did not.

In the 2 subjects (subject 1 and 7) who were unsuccessful in controlling the BCI after 5 sessions, 1 (subject1) was unable to do so despite exhibiting a clear attenuation of EEG during limb movement. Whether more training sessions would improve outcome is uncertain. The finding that Subject 8 who was unable to participate fully in BCI training because of short attention span despite a normal Abbreviated Mental Test score, suggests that more detailed cognitive screening is necessary when recruiting subjects for future BCI studies.

As the objective of this study was to use a BCI to trigger NMES of the paretic limb, the control signal had to be non-invasive and based on movement intention. The most suitable phenomenon is thus the attenuation of the mu-rhythm, which can be recorded by either magnetoencephalography (MEG) or EEG. While Buch et al has proven the feasibility of using an MEG-based BCI for chronic stroke patients [4], our findings show that, despite the poorer spatial resolution, EEG recorded over the motor cortex in acute and subacute stroke patients can also be used to control a BCI. As Buch pointed out, the use of EEG rather than MEG allows the system to be portable, and is also less expensive; these are desirable traits if such a neuroprosthesis to be used in rehabilitation centres and even in homes.

The use of EEG is not without its drawbacks. Preparation time of about ten to fifteen minutes, for matching impedances between the electrodes and scalp, makes up a sizeable portion of the duration of BCI use and invariably contributes to fatigue, and perhaps the best part of the subject's attention span is wasted. The use of impedance matching gel also requires subjects to wash their hair after each session, which is not an easy task to accomplish with one paretic arm and without a caregiver to assist them.

Although no adverse side effects like headaches or giddiness were reported, it was evident that patients were fatigued after about 45-60 minutes of using the BCI.

While the results of this study are encouraging, the following study limitations and caveats need to be highlighted. Firstly, the average time taken to trigger one BCI-activated NMES was 42 seconds which is probably longer than that achieved by conventional NMES. The timing can be adjusted for each individual, and can be further optimized. There could be, however, a trade-off between a faster response time and false-positive errors.

Secondly, subjects did not use NMES for intensive exercise in this study. For rehabilitation exercises to be effective, it should be repeated continuously for 30-45 minutes for multiple sessions, typically 3 times a week for 6 weeks, and it remains to be seen whether this is possible in this group of stroke patients.

There is also the question of whether BCI-activated NMES offers any additional benefits compared to conventional NMES or conventional rehabilitation. We hypothesize that it does, as most conventional NMES is very much a passive process with little patient engagement. BCI-activated NMES, on the other hand, is an active and engaging process that requires patients to think about moving the paretic hand, and involves mental imagery, which has been has been shown to augment functional outcome in stroke [17,18].

In summary, our results demonstrate that patients within 3 months of a stroke can learn to control a BCI and use it to activate NMES of the wrist/finger extensors. We have shown that it is thus feasible to carry out further studies, as outlined above, to evaluate the efficacy of such a rehabilitation method.

## Acknowledgment

We thank all subjects who participated in this study, as well as staff at Tan Tock Seng Hospital for facilitating the trials.

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