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ORIGINAL ARTICLE

Proof of Principle of a Brain-Computer Interface Approach to Support Poststroke Arm Rehabilitation in Hospitalized Patients: Design, Acceptability, and Usability

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Abstract

Objective: To evaluate the feasibility of brain-computer interface (BCI)-assisted motor imagery training to support hand/arm motor rehabilitation after stroke during hospitalization.

Design: Proof-of-principle study.

Setting: Neurorehabilitation hospital.

Participants: Convenience sample of patients (N=8) with new-onset arm plegia or paresis caused by unilateral stroke.

Interventions: The BCI-based intervention was administered as an "add-on" to usual care and lasted 4 weeks. Under the supervision of a therapist, patients were asked to practice motor imagery of their affected hand and received as a discrete feedback the movements of a "virtual" hand superimposed on their own. Such a BCI-based device was installed in a rehabilitation hospital ward.

Main Outcome Measures: Following a user-centered design, we assessed system usability in terms of motivation, satisfaction (by means of visual analog scales), and workload (National Aeronautics and Space Administration—Task Load Index). The usability of the BCI-based system was also evaluated by 15 therapists who participated in a focus group.

Results: All patients successfully accomplished the BCI training. Significant positive correlations were found between satisfaction and motivation ($P=.001$, $r=.393$). BCI performance correlated with interest ($P=.027$, $r=.257$) and motivation ($P=.012$, $r=.289$). During the focus group, professionals positively acknowledged the opportunity offered by BCI-assisted training to measure patients' adherence to rehabilitation.

Conclusions: An ecological BCI-based device to assist motor imagery practice was found to be feasible as an add-on intervention and tolerable by patients who were exposed to the system in the rehabilitation environment.

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Stroke is a major cause of chronically impaired arm function among adults that may affect many activities of daily living.[1] The standard rehabilitative approaches are still limited in terms of repetition, frequency, timing, and sensorimotor integration related to motor relearning.[2,3] All of these factors are relevant in promoting the compensatory functional brain network reorganization associated with motor functional recovery in the acute, subacute, and chronic poststroke stage.[4,5]

Novel rehabilitative interventions have been proposed to assist task-specific repetition, such as active forms of robot-assisted upper limb therapy.[6,7] In addition, patients' active involvment

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rewarded with performance-dependent feedback has been shown to be crucial in improving patient compliance-adherence to a given task-specific training.[8] Also, evidence exists that the patient's level of participation in rehabilitation has an impact on the outcome.[9]

In severely affected hospitalized patients with little or no residual movements, the following worst-case scenario may occur: the patient is unable to perform active or assistive exercises and is unable to spend adequate time in rehabilitation activity during recovery,[10,11] resulting in a drastically limited recovery potential. Consequently, there is an essential need for new, effective training strategies for stroke patients to match their specific needs and those of the rehabilitation professionals.[12]

Several authors have recently explored the potential of brain-computer interfaces (BCIs) for functional recovery after stroke.[13,14] The BCI technology, based on volitional modulation of the electroencephalographic (EEG) sensorimotor rhythms (SMRs) in combination with motor imagery (MI) practice,[15] robotic training,[16,17] and functional electrical stimulation,[18] has been recently promoted as a strategy to enhance motor recovery after stroke.

To effectively encourage training and practice, the BCI design should incorporate principles of current rehabilitative settings, apt to stimulate patients' engagement during a given exercise. This would be in line with recent prospective in BCI design, referred to as user-centered design,[19] which drives the assistive technology solution implementation.[20,21]

In this proof-of-concept study, we report on an EEG-based BCI system intended to support hand MI training. Our system was designed in collaboration with professional users (ie, rehabilitation specialists and therapists) to reinforce the patients' participation in this task-specific training. As such, the BCI system was endowed with a visual feedback mimicking movements of the patient's own hands to maintain consistency with the MI task,[22-27] and it was eventually intended as an add-on tool to enhance hand motor functional recovery of hospitalized patients affected by stroke. The BCI-assisted training also included the presence of a therapist to guide the patient during the training sessions, and it was introduced into a conventional motor rehabilitation setting—the hospital gym facility.

In accordance with this user-centered approach, professional users were requested to participate in the evaluation of the proposed add-on BCI-assisted rehabilitation training. The intervention was tested on a small, selected hospitalized patient sample, admitted for rehabilitation treatment after stroke, in order to describe its acceptability and usability. Following a user-centered design, we considered this preliminary evaluation as crucial for a subsequent randomized controlled trial to test the efficacy of this BCI-assisted hand MI training.

List of abbreviations:

BCI	**brain-computer interface**
BI	**Barthel Index**
EEG	**electroencephalographic**
MCID	**minimal clinically important difference**
MI	**motor imagery**
NASA-TLX	**National Aeronautics and Space Administration−Task Load Index**
QCM	**Questionnaire for Current Motivation**
QUEST	**Quebec User Evaluation of Satisfaction with assistive Technology**
SMR	**sensorimotor rhythm**
VAS	**visual analog scale**

Methods

Participants and clinical evaluation

A convenience sample of 8 patients with stroke (mean age ± SD, 60±10.9y) was recruited from a consecutive cohort admitted to Santa Lucia Foundation, Scientific Institute for Research Hospitalization and Health Care. The demographic and clinical characteristics of the patients are reported in table 1. The study protocol was approved by the local ethical board, and written informed consent was obtained from each patient. Inclusion criteria were as follows: (1) hemiplegia/hemiparesis caused by a first-ever unilateral stroke and (2) age between 18 and 80 years. Exclusion criteria were as follows: (1) previous cerebrovascular accidents; (2) concomitant chronic disabling pathologies; (3) severe arm spasticity (<4 on Modified-Ashworth Scale[28]); and (4) severe cognitive decline (Mini-Mental State Examination score <24[29]). The arm-section of the Fugl-Meyer[30] was adopted to describe intervention-specific functional improvements. A minimal clinically important difference (MCID) was set at 7 points.[31] Other clinical descriptors were adopted including the National Institutes of Health Stroke Scale[32] and the Barthel Index (BI; MCID for BI set at 14).[31,33] These outcomes of rehabilitation efficacy were evaluated by a blinded assessor at baseline and after training; however, because of the absence of a proper control condition, we report a descriptive, qualitative analysis. In line with the scope of the pilot study, the assessment of acceptability and usability was considered as the primary outcome. The adopted measures are described in a separate section below (see Acceptability and Usability Assessment section).

BCI design, signal acquisition, and training protocol

Figure 1 illustrates a training session performed with the proposed EEG-based BCI system. Patients were seated on a comfortable chair (or directly on their wheelchair) with their hands and forearms resting on a desk upon which an adjustable forearm orthosis provided support. Customized software was implemented to provide patients with real-time feedback consisting of a visual representation of their own arms and hands. The software allowed the therapists to create an artificial reproduction of a given patient's hand and arm by adjusting a digitally created image in shape, color, and size to match as much as possible the real hand and arm of the patient. This eventually led to the illusion of the patient's real hand movement when the BCI was successfully controlled. The digital image was projected over the patient's real hands covered by a white blanket. To drive the 2 states of the "virtual hand" (ie, grasping or finger extension), the BCI system exploited the EEG SMRs modulation induced by the performance of hand MI of the same movements.[34-36]

The BCI2000 software platform[a] was used for real-time estimation and classification of the SMRs state modulation and to drive the instant BCI visual feedback (ie, a cursor motion on a screen) and the corresponding "virtual hand" action. The "virtual hand" was actuated through a User Datagram Protocol connection between the BCI2000 platform and the "virtual hand" custom software.[b] As in a conventional rehabilitation setting, the patient was also supported by the presence of a therapist during the