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EEG-based Brain-Computer Interface to support post-stroke motor rehabilitation of the upper limb

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***Abstract*— Brain-Computer Interfaces (BCIs) process brain activity in real time, and mediate non-muscular interaction between and individual and the environment. The subserving algorithms can be used to provide a quantitative measurement of physiological or pathological cognitive processes – such as Motor Imagery (MI) – and feed it back the user.**

In this paper we propose the clinical application of a BCI-based rehabilitation device, to promote motor recovery after stroke. The BCI-based device and the therapy exploiting its use follow the same principles that drive classical neuromotor rehabilitation, and (i) provides the physical therapist with a monitoring instrument, to assess the patient's participation in the rehabilitative cognitive exercise; (ii) assists the patient in the practice of MI.

The device was installed in the ward of a rehabilitation hospital and a group of 29 patients were involved in its testing. Among them, eight have already undergone a one-month training with the device, as an add-on to the regular therapy.

An improved system, which includes analysis of Electromyographic (EMG) patterns and Functional Electrical Stimulation (FES) of the arm muscles, is also under clinical evaluation.

We found that the rehabilitation exercise based on BCI-mediated neurofeedback mechanisms enables a better engagement of motor areas with respect to motor imagery alone and thus it can promote neuroplasticity in brain regions affected by a cerebrovascular accident. Preliminary results also suggest that the functional outcome of motor rehabilitation may be improved by the use of the proposed device.

I. INTRODUCTION

Brain-Computer Interfaces (BCIs) collect the physical correlates of the brain activity (e.g. the Electroencephalogram, EEG), and process them in real time, with the aim of executing actions on the users environment and/or providing the user with a feedback of specific processes occurring in the brain.

Classically, BCIs have been targeted to the restoration of communication functions in individuals with severe motor disabilities, or more generally their ability to interact with the environment. Since a BCIs is based on the detection of the occurrence of physiological or pathological brain activity, it can be used to provide a quantitative measure of such cognitive processes, which can be fed to a therapist, or back to the user.

One of the most recent and promising application fields of the BCI technology targets motor rehabilitation of stroke patients [1]. In fact, the practice of motor imagery (MI) has been suggested to improve motor recovery after stroke, by inducing use-dependent plastic changes in the lesioned hemisphere [2], [3]. In this respect, EEG-based BCI systems operated via MI appear to be a promising option to promote restoration of motor function after stroke, by exploiting the neuroplasticity phenomena induced on the motor cortex by the BCI training [4].

In an effort to deploy a practical EEG-based BCI system as an effective post-stroke rehabilitation training tool, it is crucial to define which EEG patterns (sensorimotor rhythms, SMR) are expected to correlate with desirable neuroplasticity and thus reinforced through the BCI training. Moreover, to effectively encourage training and practice the BCI design should incorporate principles of current rehabilitative settings, suitable to stimulate patients' engagement during the exercise.

In addition to helping the practice of MI, a comprehensive BCI-driven rehabilitative device can also monitor the residual muscular patterns of the affected limb, and drive Functional Electrical Stimulation (FES), to close the loop between motor intention and sensory perception. The ultimate goal is to let the patients re-learn their motor scheme by having voluntary (covert and/or overt) access to the affected limb.

Two versions of the device are available, characterized by different input signals and feedbacks:

- pure EEG-based BCI, with visual feedback delivered in form of virtual hands returning the illusion of movement
- hybrid BCI (EEG + electromyogram – EMG), with multimodal feedback generated by the actual movement of the affected hand aided by FES

Both versions are meant to provide patients with an contextually enriched feedback, in order to facilitate the practice of voluntary covert and/or overt access to the affected hand. A rehabilitation intervention based on the proposed system was assessed during a clinical trial.

The rest of the paper is organized as follows. The first version of the rehabilitative device is described in Section II, where the preliminary results of an ongoing clinical trial aimed to its validation are also reported. The second

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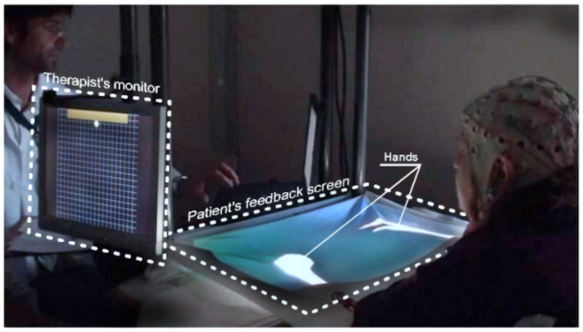

Fig. 1. Training session with the novel EEG-based BCI system. In this session, two actors take part: the patient and the therapist. The patient is trained to gain control of the visual hand representation by imagining hand movements and receives as a feedback the congruent movements of the represented hand. The therapist is fed back with the real-time movement of a cursor on a screen that is actually controlled by the patient EEG relevant feature.

version of the system is described in Section III. Results are discussed in Section IV, and conclusions are summarized.

II. BCI-BASED THERAPY WITH VISUAL FEEDBACK

A. Description of the system

Figure 1 shows the system during a rehabilitation session. The patient seats in a comfortable chair/wheelchair with hands resting on a desk in front of him where adjustable forearm orthosis provided support. Over his hands a white sheet is laid and cue and feedback for the patients is projected on this sheet with a beamer.

A dedicated software provides a visual realistic representation of the patients hands (matched in shape, colour, size), which is projected on the blanket. Different levels/shapes of lighting of the virtual hands provide an ecological cueing of the successive steps in each trial ("relax", "get ready", "start imagery", "end of trial"). The matched hand representation generates a visual illusion of hand movement each time (trial) the patient successfully controls the grasping or the opening of the virtual hand. Success or failure of each trial of the exercise is evaluated by integrating the BCI output through the duration of the trial, and comparing with a threshold defined during the calibration procedure.

The BCI section of the system processes EEG data collected from 32 electrodes (superset of the 10-20 international system, with additional sensors distributed over the sensorimotor breain areas). EEG data are conditioned (0.1–70 Hz bandpass filtering, Common Average Reference), and their spectral distribution is estimated using a Maximum Entropy Method analysis. A linear combination of features (e.g. power in a each frequency bin on a each channel) is used to build the output signal which, after an adaptive normalization, is used as a measure of the involvement of the motor cortical areas, and graphically represented as a cursor to the therapist. The subset of relevant features, and their weight in the linear combination is obtained offline from data acquired in a screening session (61 EEG channels, patient performing the same tasks as in the training). Data acquisition, online EEG processing and communication with the display software (see below) was performed by a modified version the BCI2000 software [5] .

The rehabilitation exercises including the BCI-based tool were designed in a way that the therapist-patient relationship is reinforced. In fact, the BCI-based device is meant to be an instrument in the hands of the therapist. In this sense, the training session involved two actors: patient and therapist.

During the session, the therapist is allowed to continuously monitor the patients mental activity by means of the BCI feedback (currently a moving cursor) displayed on a dedicated screen. By doing this, the therapist can verbally either reward the patient or correct his/her performing. Only discrete feedback is given directly to the patient, at the end of each trial, to avoid the development of opportunistic strategies to take control of the BCI output.

B. Methods of clinical evaluation

A prototype of the system has been installed in one of the rehabilitation wards of Fondazione Santa Lucia, and personnel (physiotherapists and EEG technicians) have been trained to use it.

1) Screening: Data were collected from 29 patients with first ever monolateral stroke. Patients were asked to either imagine (MI) or execute/attempt (ME) hand grasping with unaffected (UH) and affected hand (AH), being instructed by a visual cue. R^2 values (task vs. rest) were compiled in a channel by frequency matrix and evaluated to identify the set of candidate features that separated best rest vs. a given motor task.

2) Training: Eight of these patients underwent a MI-based BCI training as add-on to their conventional therapy, during which they were asked to control the movement of a visual representation only of their own AH by MI; training comprised 4 runs of 20 trials per session, 3 sessions per week, and lasted one month.

C. Evaluation Results

Overall, the protocol was well accepted by both patients and therapists; participation was high.

The averaged channel/frequency matrices are illustrated in Figure 2. R^2 values were higher for the UH condition (0.15 ME, 15 subjects averaged; 0.08 MI, 18 subjects averaged) than the AH condition (0.08 ME; 0.06 MI). Fig. 3 shows the grand average reactivity of SMR, before and after a one-month training, showing an increased reactivity of both alpha and beta bands. Functional outcome, as measured through three clinical scales (Fig. 4) is tendentially improved in the target group of patients with respect to the control group, which practiced the same MI task without support of a BCI. Even with small sample groups (N=8+8), the arm section of the Medical Research Council Scale reaches statistical significance ($p < 0.05$).

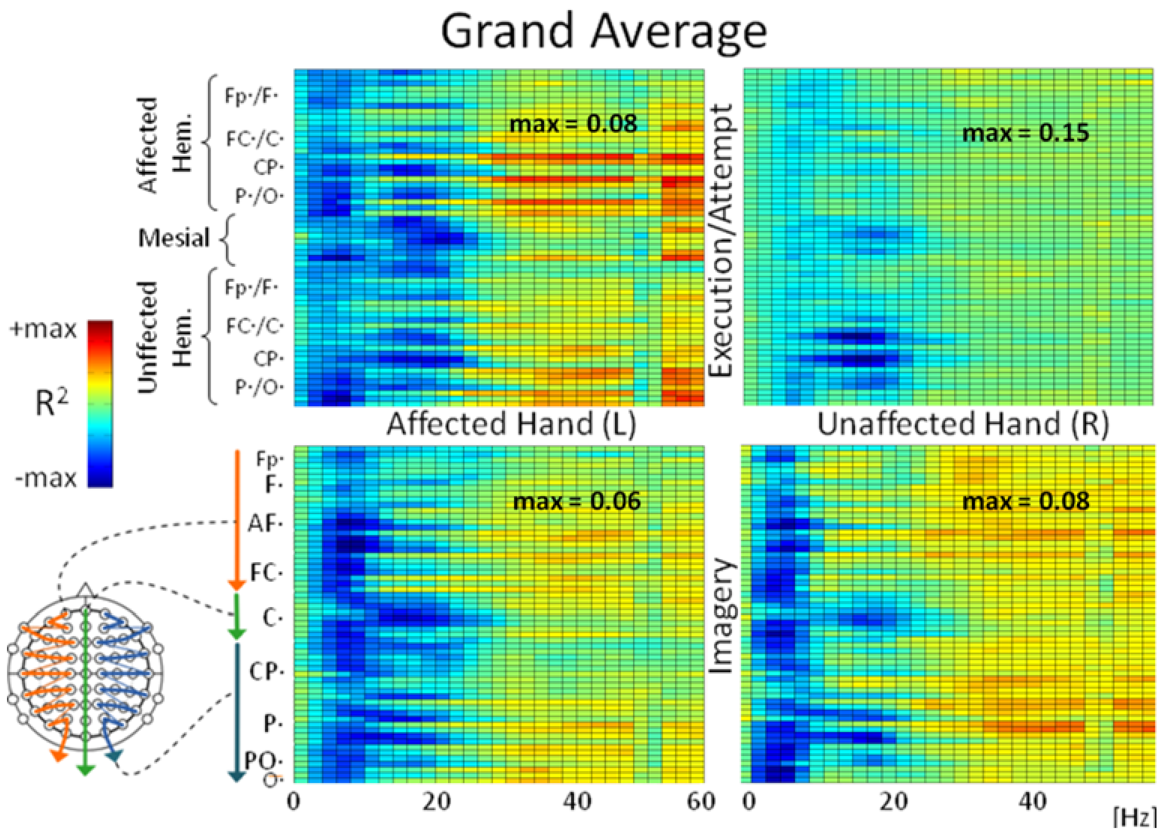

Fig. 2. Spectral changes in the EEG rhythms during hand grasping movement and imagery; grand average over 29 stroke patients. On the left and right panels, the channel/frequency matrices (horizontal and vertical axis, respectively) obtained by compiling the R^2 values averaged across patients and relative to overt and covert motor tasks are shown. Note that before averaging, the electrode positions relative to each scalp side have been flipped in order to respect the non-homogeneity of patient lesion side. According to this procedure, the top region of each panel represents the activity of the affected hemisphere; vice versa the unaffected hemisphere is represented in the bottom region. Electrodes of the midline are represented between the two, in the middle part of each panel. Colored bars code for the decrease (in blue) and increase (in red) of the EEG spectral signal amplitude, quantified by the signed R^2 values scaled on the right side of the bars.

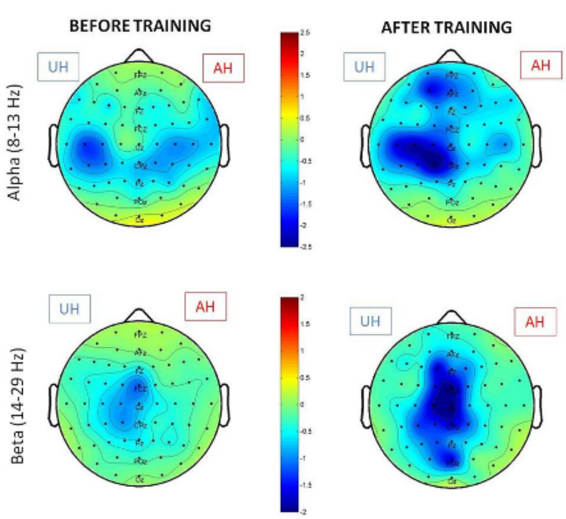

Fig. 3. Grand average (N=8) of significant spectral power changes (color coded) of EEG rhythms between task and rest conditions, before (left panels) and after (right panels) one month training with the BCI-based device. Top row: alpha band; Bottom row: beta band.

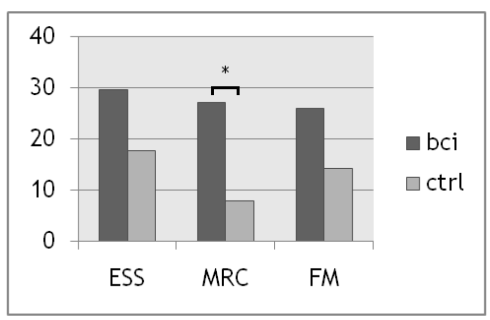

Fig. 4. Relative changes (before-after training) of clinical functional scales evaluated in the group (bci, N=8) trained with the BCI-based tool, and in the control group (ctrl, N=8). FM: arm Fugl-Meyer scale (arm F-M); ESS: European Stroke Scale; MRC: arm section of the Medical Research Council Scale). All scales show a trend in favor of the BCI group.

III. HYBRID BCI-BASED DEVICE WITH MULTIMODAL FEEDBACK

A. *Overview of the system*

The second rehabilitation device relies on a hybrid BCI, i.e. both EEG and EMG are fed into the BCI. Modularity of the hybrid BCI was specifically taken into account, through extensive use of standardized interfaces [6] between processing modules. A unique stream of biosignals (formatted according to the specifications of the The TOBI Interface A – TiA) is created by a Signal Server, which collects data from three 16-channels biosignal amplifiers (gUSBamp, g.Tec, Austria). TiA strams are simultaneously fed into two parallel processing pipes, which deal with EEG and EMG signals respectively. The output of these elemental BCIs is formatted according to the TOBI interface C (TiC) format, and fed into a fusion module, which (i) implements the rules according to which the feedback is given to the patient, and (ii) forwards several relevant time series to the therapist's screen.

The EMG classifier is implemented in Matlab, and features similar connections as the EEG classifier (TiA from the Signal Server, TiC to the Fusion Module). The Fusion Module, also implemented in Matlab receives classification outputs from both the SMR and the EMG classifiers, and transforms them into "fusion classes" that manage the FES Controller. The patient is delivered a Functional Electrical stimulation which induces/assists the correct motor exercise required by the therapist (finger flexion or extension). Fig. **??** shows an overview of the software and hardware hybrid system.

B. *Classification and fusion of EEG and EMG data*

The EEG processing pipe is substantially identical to the one described in Section II. The output signal measures the involvement of motor areas in the imagined/attempted motor exercise.

For EMG classification, extraction of the Linear Envelope is used to obtain a signal that is directly correlated with the strength of contraction. Four muscular groups are considered – flexor and extensors of fingers, flexor (biceps) and extensor (triceps) of the arm. The pattern of muscular activation is considered to be correct if the normalized[1] total intensity of muscular contraction of extensor (flexor) muscles exceeds the intensity of antagonists, in a extension (flexion) task by a specified threshold. In other words, stiffness or other non-physiological muscular patterns are discriminated from physiological activation patterns, and this discrimination is quantified by the output of the processing pipeline.

Only when both conditions happen simultaneously (involvement of motor cortex, and physiological muscular pattern) at the right time (within the "trial"), the fusion module consents the activation of the FES, which in turn constitutes a positive reward for the patient.

IV. CONCLUSIONS

As previously shown [4], a motor imagery-based BCI training is suitable to induce post-training cortical plasticity as revealed by an increased motor evoked potentials recorded from hand muscles after stimulation of cortical motor areas with Transcranial Magnetic Stimulation (TMS). The BCI-based rehabilitation tool described in Section II is currently installed in the ward of a rehabilitation hospital and allows stroke patients to perform daily sessions in which they practice MI of simple movements of their paralyzed hand, by controlling a visual representation of their own hands. Both clinical and neurophysiological assessment of the first 8 stroke patients who underwent a one-month BCI-training with this system revealed encouraging results (compared to an equal sized control group) for the future introduction of the BCI technology-assisted intervention in large scale clinical programs for stroke rehabilitation. To our knowledge this is the first randomized controlled trial carried out to evaluate the efficacy of the mental training of motor skills (motor imagery, MI) supported by an EEG-based BCI device to promote recovery of hand function after stroke.

In the hybrid version of the BCI-based rehabilitation device, the screen on the desk is removed and patient eventually observes his/her own hand move thanks to FES-orthosis controlled by the hybrid-BCI. By leveraging both cognitive functions and the residual motor ability of the patient, this device provides for a comprehensive support to rehabilitation of upper limb.

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[1] Absolute intensity of EMG intensity depends on muscle size, inter-electrode distance, and other factors. The intensity during maximal voluntary contraction is utilized as a normalization factor