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Brain-Computer Interface Systems in the Rehabilitation of Chronic Stroke Patients with no Cognitive Impairments

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Abstract

In post-stroke motor rehabilitation of the upper limb, Brain-Computer Interfaces (BCIs) are becoming widespread complementary tools of the standard clinical practice to reinforce the beneficial effects of the treatments administered during the hospitalization. This kind of systems takes advantage of the so-called *neuroplasticity*, an exciting – but sometimes controversial – property of the brain that allows the recovery of lost functions by substituting the use of damaged neural paths with alternative ones, usually redundant.

BCIs then artificially induce patients to unconsciously modify their cerebral activity to identify and reinforce – with a specific training – such new paths. Operant-conditioning is the most employed strategy for realizing this artificial learning and its effectiveness mainly depends on the reliability of the features that drive the BCI. After a brief excursus on the standard rehabilitative methods, an example of BCI application is presented with a following discussion about strong points and criticisms to cope with yet.

Keywords: *Stroke, motor rehabilitation, arm, upper limb, EEG, BCI, reaching, operant-learning, neuroplasticity.*

1. Introduction

Stroke is one of the leading cause of mortality in the world and most survivors unfortunately remain with severe impairments that preclude them to live a normal life, needing a twenty-four-hours care assistance.

International guide lines have been established for the best clinical practise of post-stroke management and rehabilitation. In particular, activities like reaching and grasping are among the most useful motor function affected by this cerebrovascular disease. Therefore, a special care for their recovery is taken and literature suggests that high-intensity, repetitive and goal-directed training are highly beneficial, along with manipulations and physical therapy.

Besides these standard methods, new approaches have been tested and found to be effective: among others, Brain-Computer Interfaces (BCIs) have showed promising results and are expected to bring further improvements thanks to a rapid development of technology.

2. Stroke and Neuroplasticity

World health reports [1] usually show severe traumatic neural injures, particularly stroke, as the second or third most common cause of mortality in the majority of the Countries of the world. This clue is constantly increasing with the ageing of the global population and with the worsening of food habits and environmental conditions of life. Clinically speaking, stroke can be caused by an ischemia or an hemorrhage. In the first case, the most common one with an occurrence of the 87%, an interruption of blood feeding to a part of the brain occurs while in the hemorrhagic stroke a blood loss injures the surrounding cerebral tissues. As a result, in both the cases, this cerebrovascular disease causes – if not death – mild to severe impairments affecting the functions normally performed by the damaged areas of the brain.

By now it is well-known that after stroke spontaneous processes [2], [3], [4] of recovery take place: synapto-genesis increase, dendritic branching along with neural sprouting have already been observed and are currently under deep investigation all over the world. These changes inside brain are generally referred as *neuroplasticity* [5] and can be addressed as promising prognostic clues of the best recovery towards health. Literature [6], [7] highlights also the effectiveness of a high-intensity, repetitive and goal-directed training: the latter indeed have been correlated with advantageous changes in the neural architecture. Thus, activities like occupational therapy are highly recommended by all international guidelines for the best clinical practice for stroke rehabilitation.

3. Rehabilitative Methods

International guidelines [8], as mentioned above, establish the importance of task-specific and intense training that promote neural plasticity and spontaneous recovery of lost functions. Moreover, manipulations by the physical therapists, pharmacological treatments and physical therapies with lasers or magnetic fields are also typically included in every rehabilitative programs for post-stroke patients [6], [7].

Besides this kind of standard therapies, many other alternative and more innovative methods [6], [7] have already been used and have shown their effectiveness in promoting beneficial anatomical and physiological changes in the brain. Among others, bilateral training was introduced to induce patients to regain lost functions of their affected limb taking advantage of the comparison of the healthy one.

On the contrary, constraint-induced therapy forces patients to use the only affected limb, since the healthy one is immobilized. Another major class of rehabilitative methods includes some kind of feedback in their protocol: for instance, while a patient is performing an exercise of isotonic contraction of his/her hand, a feedback of his/her muscles activity is measured by an electromyogram (EMG) and shown to the patient. On its turn, the latter has to adjust the effort of the contraction following the information provided by its own EMG. During Virtual Reality training, instead, correct motor behaviors are fedback by real-world scenes in a virtual environment such as a kitchen, a bar or a supermarket. All these kinds of feedback-supported trainings have been showed to be effective to make patients improve their motor abilities and to cope with the annoying repetitiveness of the training exercises.

A final particular class of recovery strategies has to be mentioned: the Motor Imagery one. During motor imagery tasks the patient has to imagine the movement of a limb or a hand, a foot or even the tongue. When his/her cerebral activity is then recorded and used to provide him/her information about the quality of his/her performance or to control an external device, a kind of brain-computer connection is established. Brain-Computer Interfaces (BCIs) are indeed the youngest motor rehabilitative methods but they have already showed their effectiveness and potentialities.

4. Brain-Computer Interface in Motor Rehabilitation

Originally implemented to provide an alternative communication channel to completely paralyzed people [9], [10], from the 90s BCIs have been reviewed as tools to complement or totally substitute damaged parts of the body to recover lost motor functions in severely impaired people with intact cognitive functions [11], [12], [13]. A large amount of literature has already been written and many BCIs laboratories were found all over the world.

In particular, the most important and referred BCI centers are mainly located in USA and Germany: the Wadsworth Centre in New York, for example, is led by Jonathan Wolpaw and many other researchers that made significant contributions to the advancement of this kind of technology.

The Donoghue's Lab in Providence led by John Donoghue is mainly focused on the development of invasive BCIs that collect the cerebral activity by means of microarray of electrodes and microelectrodes grids implanted inside brain or from electrodes placed over the cortex by means of electrocorticogram (EcoG).

Tubingen, instead, owes its popularity to Niels Birbaumer, who was the first BCI researcher that succeeded in making a completely locked-in (CLI) patient to send him a message through a non-invasive BCI system in 2000 [10]. Since now, many other kind of patients were recruited in several experimental BCI platforms: persistent vegetative state patients (PVS), children suffering from attention deficit hyperactivity disorders (ADHD), severe stroke and spinal cord injured (SCI) subjects have already operated different types of BCI [11], [13], [14]. A non-invasive BCI can indeed be driven by electrical or magnetic signals collected outside brain by means of an electroencephalogram (EEG), magnetoencephalogram (MEG), functional near infrared spectroscopy (fNIRS) or functional magnetic resonance imaging (fMRI) scanners. With their own strong points and drawbacks, all these methods were tested all over the world, but no one has already really outperfomed the others.

A particular kind of EEG-based BCI was implemented by Pfurtscheller and colleagues in Graz (Austria): in fact, Pfurtscheller defined [15] and exploited in a BCI system for the first time the so-called *movement-related desynchronization* (MRD) phenomenon. The latter can be identified by a simple EEG when a subject performs, observes, imagined or even plans a movement: specifically, during this kind of tasks the power of the EEG signals recorded over the sensori-motor cortex – a tiny strip between the frontal and the parietal lobe (see Figure (1)) - in the frequency bands around 10 Hz – namely, μ rhythms – and around 20 Hz - β rhythms – considerably decreases as compared to the analogous quantity computed in a relaxed period when the subject is at rest. This is a reliable phenomenon suitable to drive a BCI: it is quite easily identifiable and most people shows it during motor tasks.

For this reason this characteristic cerebral activity was also chosen to drive the BCI platform implemented [13], [16] at I.R.C.C.S. San Camillo Hospital Foundation in Lido of Venice for the motor recovery of mild impaired stroke survivors without cognitive deficits hospitalized at the Institute.

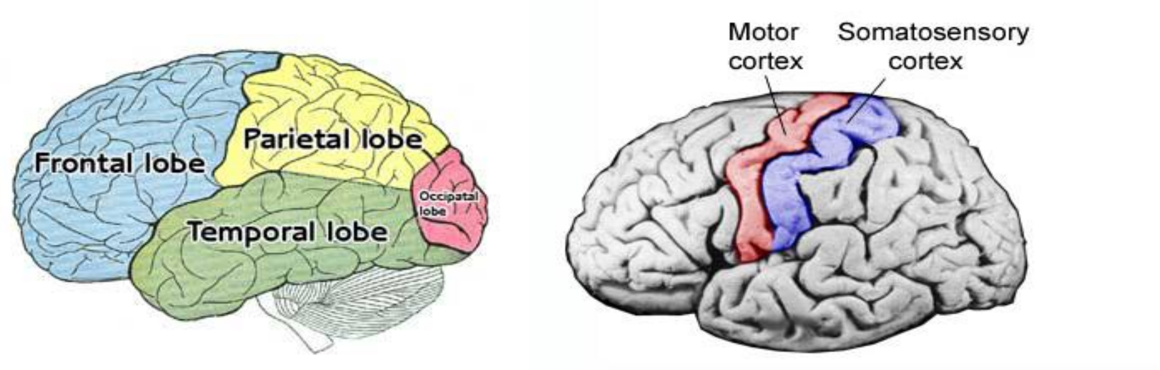

Figure (1): Anatomy of the human brain: main lobes and sensori-motor areas

5. The San Camillo BCI application for Stroke Patients

As detailed described in [16] the BCI platform implemented at the IRCCS in Venice follows the typical BCI structure defined by Wolpaw and colleagues in [12]. The actual setup is captured by Figure (2) where the four classical steps are labeled.

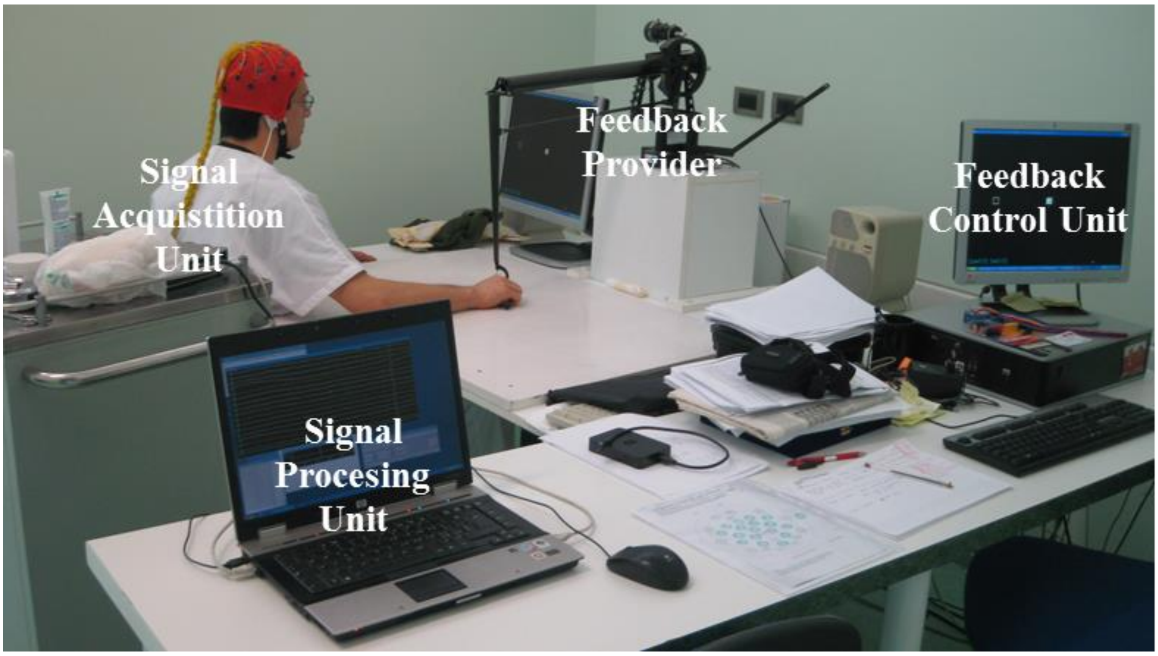

Figure (2): BCI setup

As shown in the picture, the subject is sitting on a comfortable armchair holding the end-effector of the robotic arm named Phantom [17]. After 40 seconds of rest, his task is to hit a target that randomly appears at one out of four cardinal points of the screen placed in front of him. The subject receives acoustic and visual feedbacks that guide him in performing the motor task. Besides that, he is also fedback of his own cerebral activity: in fact, an EEG system made by 21 electrodes cap and a 16 channels gTEC amplifier [18] records his activity from 16 locations chosen among the 21 electrodes of the cap to best cover the sensorimotor areas of the scalp. Then, the signal processor which runs the world-wide spread software BCI2000 [19] extracts, in real-time, some relevant EEG features that characterize the patient's status along the experiment. Specifically, the MRD is quantified during each trial and a force feedback is provided to the subject by means of the Phantom device: whenever the patient is correctly performing the reaching task he receives a force help for completing the movement. This feedback strategy represents the reward of a standard *operant-conditioning* [20] method of learning. In fact, repeating this kind of exercise for several times patients learn to use healthy alternative neural paths surrounding the stroke damaged area of their brain to control the movement of the contralateral limb. This has already been proved [21],[22] to be effective for improving the motor abilities of these patients. Indeed, after two weeks of training, the patient recruited till now in the experiment showed kinematic improvements along with a clear presence of MRD in his sensori-motor areas. A brief summary of these results is provided by Tables (1) and (2) where the number of correct trials, the mean duration of a trial and the area error between the ideal straight trajectory from the starting position to the target and the actual path are reported.

Table (1): Kinematic results before and after BCI treatment of the patient. Left affected arm

Test type	Correcttrials [%]	Meanduration [ms]	Area error [mm^2]
Initial test	15 ± 5	902 ± 244	35 ± 3
Final test	28 ± 5	811 ± 27	33 ± 7

Table (2): Kinematic results before and after BCI treatment of the patient. Right healthy arm

Test type	Correcttrials [%]	Mean Duration [ms]	Area error [mm^2]
Initial test	31 ± 3	808 ± 313	23 ± 6
Final test	39 ± 1	729 ± 136	22 ± 1

Moreover, Figure (3) and Figure (4) show the mean energy of the μ rhythms before and during the movement.

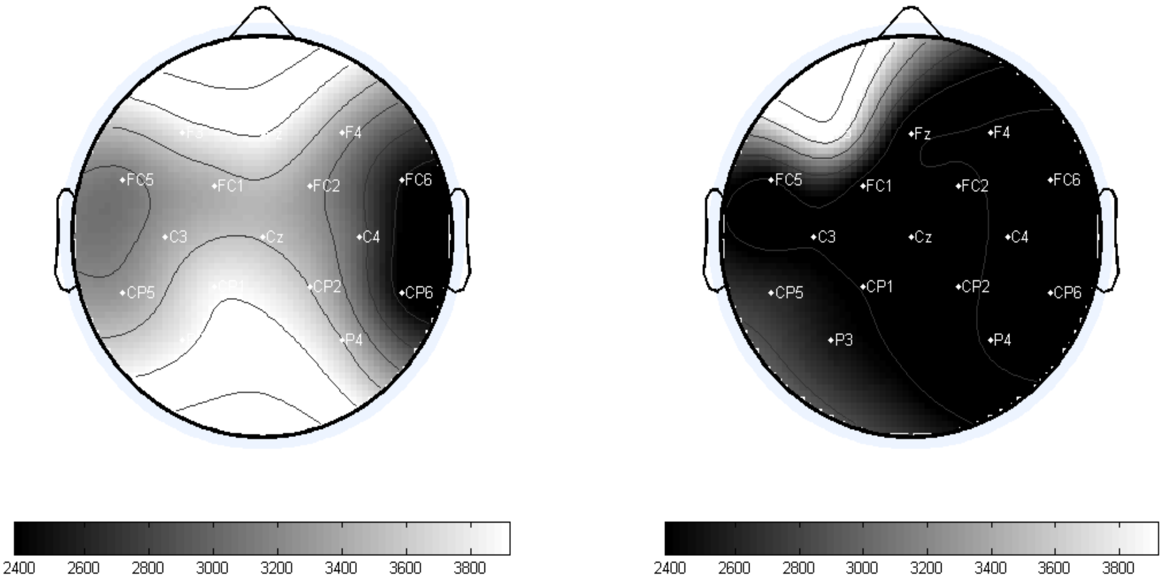

Figure (3): MRD of the patient during left affected arm movements (left panel: rest; right panel: movement).

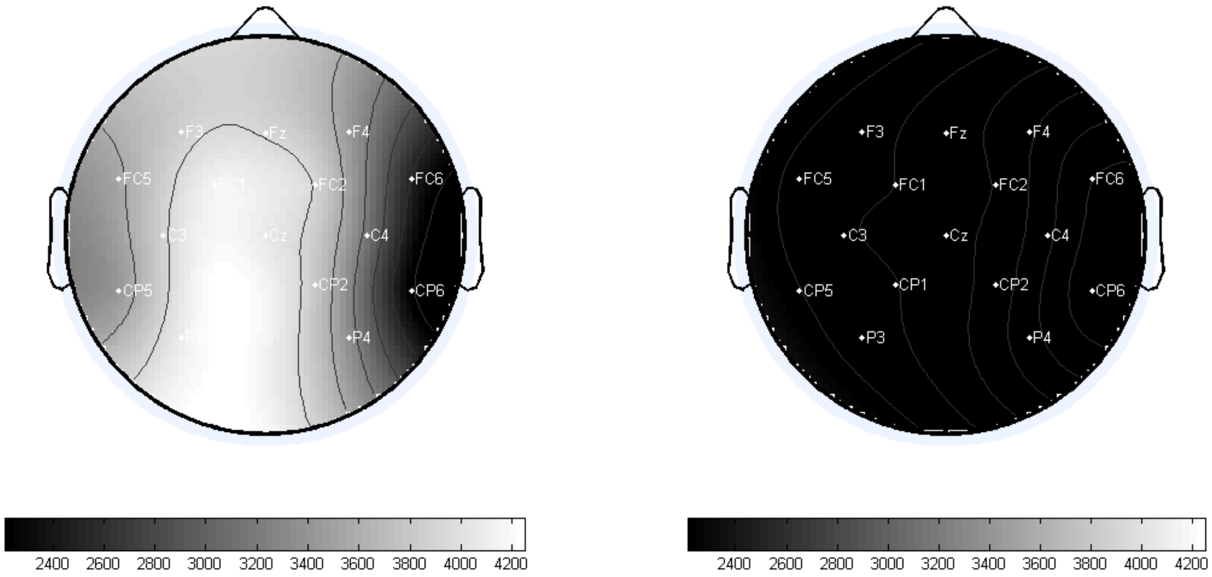

Figure (4): MRD of the patient during right healthy arm movements (left panel: rest; right panel: movement).

6. Discussion

As mentioned above and clearly visible from data provided in Tables (1) and (2) and in Figure (3) and (4) the patient improved his motor performance using this particular BCI setup where the desynchronization of the sensori-motor rhythms – particularly, the μ frequency band – in the sensori-motor are as of his brain is transformed into a target-directed force that helps him in ending up the reaching task.

These preliminary results cannot finally ensure the overall effectiveness of this BCI platform, but they are promising on the way towards a completely recovery of motor functions of this kind of patients. Moreover, it has to be mentioned that this experiments not a fully-automated procedure but, on the contrary, a relevant element of the systems defined in an almost totally qualitative way: in fact, the choice of the EEG feature is performed on the basis of the estimations of the MRD gathered by BCI2000 with the support of a very scarce literature about this particular BCI application.

However, this experiment is the very beginning implementation of such a BCI for the rehabilitation at I.R.C.C.S. San Camillo and new algorithms are already being currently developed to bypass the encountered criticisms of the system and, consequently, further improve its effectiveness.

7. Conclusion

The paper presented stroke as one of the most world-wide spread injuries nowadays. Following to a brief digression on the basic neuroplastic spontaneous mechanisms that begin suddenly after the stroke event and the description of the most common rehabilitative therapies, the paper dealt with a particular kind of Brain-Computer Interface implemented at I.R.C.C.S. San Camillo at Lido of Venice for the motor recovery of mild impaired chronic stroke patients with no cognitive difficulties. Some preliminary results assess the promising potentiality of this platform.

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