A Motor Imagery based Brain Computer Interface to restore upper limb movements

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***Abstract*—Spinal Cord Injury (SCI) is a condition that causes, for patients suffering from it, a huge lack of autonomy. This is very expensive, both for families and society, as people are often totally dependent on others also for the most basic and everyday situations. In the recent years lot of investments have been made for improving their lifestyle and autonomy. Although several different approaches have been developed for many BCI systems, we decided to implement our own setup for SCI patients based on MI literature, and in particular on MI training before the actual use of the BCI. Studies revealed that in SCI there are several departures from healthy subjects brain patterns, along with other preserved motor functions. We analysed these brain activation patterns for upper limb movements and we developed both a non-invasive and an invasive BCI system. The former is based on FES, electrical stimulation of arm and hand muscles, and the latter on an implanted device called *bridge*, which aims to restore the damages in the spinal cord bypassing them. Supported by the literature, our results seem promising and we now expect to implement the actual system and start the clinical trial.**

***Index Terms*—Motor Imagery, Brain Computer Interface, Spinal Cord Injury, Upper Limbs, Functional Electrical Stimulation, Bridge**

I. Introduction

A Spinal Cord Injury (SCI) is an event that causes in patients problems and disturbances in normal sensory, motor and autonomic functions [1]. Events which lead to SCI may be traumatic, such as car crashes, work-related or sports accidents, but also non-traumatic, caused by diseases or degenerations from pathologies, like cancer. While the former cause refers to almost the 90% of the cases, the latter appears to have an increasing rate in recent years [2].

According to the World Health Organization (WHO), every year around the world we face between $250\,000$ and $500\,000$ new people suffering from a SCI, which is an incidence of around 40 to 80 cases per million population [3]. Most of the patients affected by a SCI are men ($\sim$80%) and we are facing a steadily increasing trend in the age at the moment of the injury: from 29 years during the 1970s to 42 years nowadays [4].

Despite the incidence may seem relatively low, the costs underlying this health condition are very high, especially for the most severe forms of the injury; they represent one of the major issues when facing the problem, not only for the patient itself, but also for families and caregiver institutes [5]. In fact, we must consider both direct and indirect costs when facing this kind of analysis. We need to take into account hospitalization and rehabilitation costs, but also the fact that people suffering from a SCI are likely to be excluded from participation in society, with high unemployment and school-dropping rates [6].

Therefore, a global effort in the research field is being done, in order to find suitable solutions that may possibly lead to a reduction of costs and an improvement on the quality of life of people affected by this trauma.

The severity of the symptoms depends on the lesion and its location in the spinal cord; it may concern arms, legs or even the whole body. Most of the patients suffers from neurological injuries at the level of $C4$ and $C5$ and they experience a reduction or, in the worst case scenario, a complete loss of functions (motor and autonomic) below the level of lesion [7]. When the $C5$ cervical vertebra is interested, finger functions are lost or damaged, while when the lesion is higher, at the $C4$ vertebra, additional hand functions and elbow flexion are limited.

The result is a wide reduction in autonomy and a consequent strong dependence from caregivers or families, even to accomplish the simplest tasks. Priorities of rehabilitation systems are, therefore, to give of those suffering from SCI an higher degree of self-sufficiency in everyday tasks, for activities like grasping or reaching [8].

The Brain Computer Interfaces (BCI) field aims to improve this aspect of the rehabilitation: multiple studies ([9], [10], [8]) highlight how the use of BCI may help patients to restore abnormal brain patterns and thus voluntary control movements via brain signals. Also, especially with invasive solutions, BCIs show the possibility of bypassing the area of damage which causes disconnection of transmissions.

In this study we focus on the use of Motor Imagery (MI) to prevent and restore abnormal patterns in brain functions for patients suffering from SCI. fMRI studies show that, despite many normal motor functions are preserved in these patients, there are also several departures from patterns of healthy subjects [11]. These abnormalities may be reduced with the use of MI training [12].

We aim to analyse the effect of normalizing these brain motor functions that affect SCI patients prior to the training for the restoration of movement, in order to investigate the possible benefits in the rehabilitation. This represents a novel approach in the field, and may lead to better and more effective solutions for patients.

This study is focused on the improvement of upper limbs functions, i.e. grasping and reaching, using first MI to restore the abnormal brain patterns. Results and possible improvements obtained with this method are investigated by comparing the training for the restoration of movement in patients that achieved the normalization of brain patterns through MI before the training, and patients who did not. We also analyse the possibility of using an invasive BCI that, by the direct implantation of electrodes, works as a bridge in the spinal cord to bypass the area of the lesion.

The paper is structured as follows: in Section II we decribe the MI training and its experimental setup, in Section III we present the background in the BCI field and our design choices, in Section IV we describe the electrode placement, the preprocessing and the features extraction phases in our BCI system, in Section V we explain the classification of the features using a Support Vector Machine (SVM), in Sections VI and VII we present two methods to restore the upper limb movement, one based on the Functional Electrical Stimulation (FES), and one intrusive, based on an implanted device called "Bridge". Finally, in Section VIII we draw some conclusions and highlight possible future improvements and works for our BCI system.

II. Motor Imagery Training

As neuroscience-based rehabilitation has gained momentum improving recovery in the most wide situations [13], it is important to understand how this technique acts on brain neuroplasticity. This is done in order to develop rehabilitation strategies which achieve the best outcomes.

Brain activation patterns for patients suffering from motor impairments have been widely studied ([14], [15], [16]). However, if we focus our attention on SCI, studies revealed that several brain motor functions appear to be preserved even in chronic complete SCI ([17], [18], [19]), but there are also several departures from healthy subject's patterns. Among these, we may cite a strongly reduced volume of activation, poor modulation of functions and abnormal activation patterns [11]. To prevent such abnormalities, MI, which is described as the imagination of moving specific body parts without any motor output, has proven to be useful ([12], [20]). Despite most of the studies focus on the analysis and restoration of patterns for lower limbs imagined movements, there are proofs of the efficiency of MI in improving motor output capabilities of upper limbs for SCI patients, such as hand functions, movement time and hand trajectory smoothness ([21], [22]). A study by Turner et al. [23], moreover, based on functional MRI measures of somatotopy following SCI, showed evidence of functional brain reorganization of active brain areas during upper limb's tasks.

Based on the evidence that MI induces brain adaptation and improvements also in upper limb's reach-to-grasp performance, as proved by Mateo et al. ([24], [25]), we decided to implement a MI training step before the actual BCI training. This is done in order to achieve a normalization of brain motor system functions related to the movement of the paraplegic limb involved in the following BCI setup. Results of adopting this technique are assessed by a comparison between the efficiency of the following BCI training of patients that achieve an improvement with MI training, such as a reduction of the abnormally increased brain activity, and patients who do not. A fMRI assessment before and after 7 days of MI training to the arm and hand movements is performed to address whether increased fMRI activation is present after training.

A. Experimental setup and methods

Subjects for the study are selected with injury at the level of $C4/C5$ cervical vertebrae; they present a reduction or a complete loss of upper limb functions below the level of the lesion, but with nerves and muscles not damaged. Before the starting of the study, they are asked to complete a questionnaire to address whether contraindications to MRI or additional neurological diagnoses are present, which represent exclusion criteria.

The part of the study involving MI training is articulated in three steps:

1) initial fMRI evaluation;
2) MI training lasting for 7 days;
3) fMRI evaluation after training.

In the first step, videos showing the exact movement to be performed or the resting state are shown to the patients. They show a hand reaching a cylindrical object on a table, a hand grasping the same object and a hand at resting state on a table (Figure 1), which represent also the same movements that the BCI aims to classify and restore in the second part of the study. Based on images of the three tasks shown on a monitor and vocal commands, during MRI scanning patients are then asked to attempt the movement of the arm, regardless of the actual ability to move the limb. The instructions are organized in 30 seconds blocks for each task, with a new image showing a different object every 5 seconds.

In the second step MI training is performed, with the same tasks and images used in the first step. Patients are asked to train for two times a day for 60 minutes, executing the MI task with closed eyes following the vocal commands. They are recorded by a camera during the performances and periodically contacted to check mental and muscular fatigue, which can alter performances [26], or possible errors in the training methods.

After the one-week training the third step with the final fMRI evaluation is performed, with the same modalities occurred in the first step.

B. Data analysis

A subsequent data analysis is performed, to extract several measures such as volume, location, and magnitude of activation. This is taken into account in the following steps of the study, during the development of the BCI system, in order to evaluate the possible benefits of this previous training.

Fig. 1: *The image on top shows the resting task, the central one the reaching and the one in the bottom the grasping movement to be performed*

III. BCI

Direct communication between brain and computers is one of the faster growing field in neuroscience, both for development and research. Effectively it is a BCI, the device allowing us to bypass the user's natural output channels for peripheral nerves and muscles, and communicate or control other artificial devices [27].
Usually, a BCI works in real time, analysing the electrical signals recorded from electrodes on the scalp, and recognizing the user intent.
Namrata and Mattu in 2016 published a survey about the priorities of spinal cord injured population [28] N=71. The patients were paraplegics and quadriplegics and the results are:

- Quadriplegics priorities:
  - 60%, regaining arm and hand function;
  - 26%, regaining control of the bladder and bowel;
  - 7%, having more strength in the upper body/trunk;
  - almost 0% priority for sexual functions;
  - the remaining priorities are related to walking movements and the elimination of chronic pain.
- Paraplegics priorities:
  - 63% regaining control of the bladder and bowel functions, elimination of autonomic dysreflexia[1];
  - 12%, having more strength in the upper body/trunk;
  - 3%, sexual functions;
  - 9%, walking movements;
  - the rest was elimination of chronic pain.

This studio underlines how important it is, for both the categories, to restore everyday normal tasks. In our paper we will focus in the arm and hand function rehabilitation in particular.
We decided to build our BCI around MI because of the promising results and some secondary effects that can improve users health [29].
As reported by Varkuti et al. [29], using MI means gaining better Functional Connectivity Changes (FCC) and this is equal to have stronger Functional Connectivity (FC) improvements. On the other hand, MI requires a longer and more effective training because the standard deviation in accuracy is usually higher with respect to other methods [29].

IV. Experimental setup and processing

A. Electrodes placement

The recording of the signal can be done through different combination of electrodes placement. For SCI-MI the most suitable solution is adopting the 10-20 or 10-10 international systems. Even if these configurations are made by high number of electrodes, the information recorded by sensors $C3$ and $C4$ (together with the reference electrode Cz) is enough to discriminate voluntary thinking related to MI [30].
We decided to adopt the 10-20 configuration, with 21 electrodes (Figure 2). For the data processing the sensors used are the $C3$ and $C4$, along with the reference electrode and the ones responsible for ocular artefacts, which have a large influence on EEG signals. To avoid them, when a transition greater then 25 μV is found, all the EEG samples recorded in the following half second are not taken into account [31].

B. Bands and artefacts

The EEG signal is a source of different kind of information. It can be affected by a huge number of artefacts and it allows us to analyse information related to different conscious and unconscious activities.
When the purpose is MI, for recovering lost abilities or train some prosthesis, the focus of the analysis is the range of

[1] acute, uncontrolled hypertension.

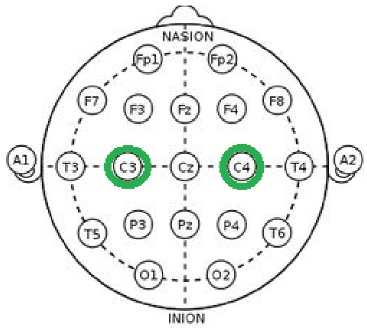

Fig. 2: *Representation of the used electrodes. Figure adapted from Wikimedia Commons.*

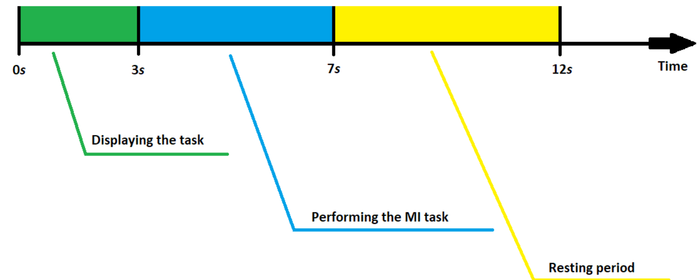

Fig. 3: *Visual representation of our time acquisition pipeline.*

frequencies from 4 to 30 Hz of the EEG signal. In particular, we are interested in 2 different bands, the μ band and the β band, 8-12 Hz and 14-18 Hz respectively. Nevertheless, to perform the processing it is preferable to use all the information in each 1 Hz band, rather than fixing the two bands a priori. We made this choice for gaining adaptability with different users [32]. The sample frequency is usually fixed at 128 Hz, 256 Hz [33] or 512 Hz [32]. We use the latter, which allows us to have a suitable time resolution.
In our system we use a noise removal notch filter at 50 Hz, in order to remove artefacts due to power line.

C. Features extraction

To generate the features that feed the classifier, the computation of the Power Spectral Density (PSD) for the aforementioned bands is required. The signal that has to be extracted is related to the imagination of performing some kind of tasks. In our case they are the resting, reaching and grasping tasks. The recording phase is organised in sessions. Each session is made of 20 trials for each task. Images of the tasks to be performed are randomly shown to the patient, following the temporal diagram delineated in Figure 3: the images last in the screen for 3s, the patients have to perform the MI task for 4s and at the end 5s of rest. They are asked to imagine the movement without any output feedback. The EEG signal is recorded and discretized in samples. These samples are grouped in different sets. Each set is related to the different time window in which its samples have been recorded. Only samples belonging to the interval of time in which the MI task is performed (i.e. from 3s to 7s) are taken into account for the features generation.
Computing the PSD for each time window set, the features extraction can be performed. The PSD computation is done because the recognition of different patterns in human though (especially related to MI) is more convenient when computed in the frequency domain.
In order to avoid the loss of time information, the Morlet wavelet scalogram is used (Figure 4). Thanks to the mother wavelet $\lambda(t)$ and to the shift property of the Fourier Transform, it is possible to combine the different energy contributions from different bands, into a single feature. The best choice for the shifting parameters has been made with the support of a 10-Fold Cross-Validation. The domain change from time to frequency is computed following these steps:

- convolution of the EEG sampled signal $x(t)$ with a windowing function (belonging to mother wavelet family), shifted of a well defined quantity (that represents time) t_0;
- computation of the Discrete Fourier Transform (DFT) of the result from the previous computation through some well known algorithm (e.g. FFT). In this way a Time-Frequency representation of the signal is obtained;
- calculation of the Marginal Energy:
$$E_f = \sum_t \mid X(f,t) \mid^2$$
- energy of the band E_B obtained as the sum of all the Marginal Energies belonging to the considered band:
$$E_B = \sum_{f \in B} E_f$$

Finally, the feature is the log-transform of the energy E_B previously obtained for each band. [32].

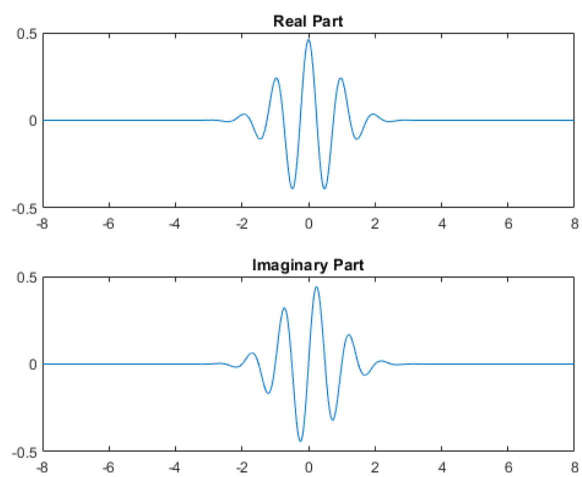

Fig. 4: *Representation of the used electrodes. Figure adapted from Wikimedia Commons.*

D. ERD/ERS

For the analysis of the features extracted from the power spectrum, we are using as discriminants in the classification what are called Event Related Desynchronization and Synchronization (ERD and ERS).

It is known that during MI and intended or actual movement there is a decrease in μ and β bands rhythms, the ERD [34], whose degree might be associated with an increase in neural activity [35]. As the patient needs time to react to the stimulus and start performing the movement, the desynchronization does not start at the very beginning of the MI task, but some milliseconds after it, and ends about 1s after stopping the imagination.
We can also measure an increase in the β rhythm and this happens after the actual, intended or imagined movement is executed: this is the ERS.
Both ERD and ERS are located in the sensorimotor cortex and, more precisely, in the contra-lateral region. Therefore, they can be detected considering the $C3$ and $C4$ electrodes in the scalp.
In Figure 5 we can see an example of the time course for ERD and ERS, averaged with all the participants to a study by Yong et al. [36], for different imaged motor tasks, similar to the ones analysed in our study.

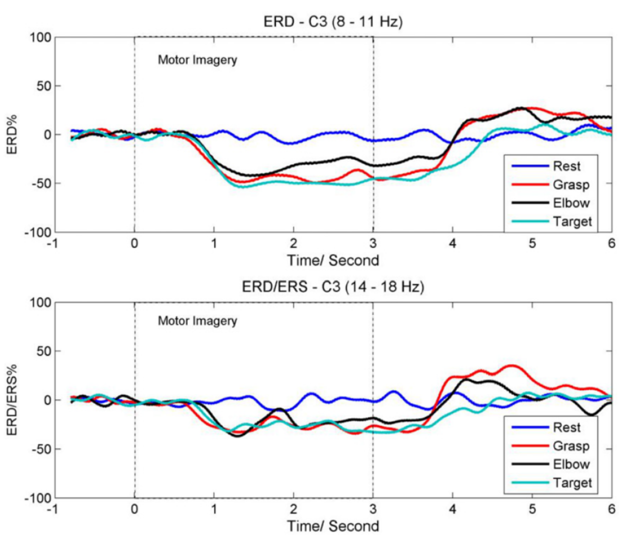

Fig. 5: *The average time course for ERD and ERS. Figure taken from [36].*

V. SVM

A. General model

In order to classify the features previously extracted, we decided to use a Support Vector Machine (SVM) classifier. This kind of supervised learning machine is very efficient and provides good results if we compare them to the ones obtained with other classifiers, such as logistic regression (LR) or Linear Discriminant analysis (LDA) [36].
The SVM classifies input patterns received from the pre-processing phase: these patterns are a collection of features, which represent the EEG signals previously recorded from the users. Projecting these sets of features in a feature-dimensional-space, made by a variable number of hyper-planes (one for each class investigated), the SVM checks the belonging class for each pattern, trying to minimize the *generalization error*.

B. Our SVM

The general SVM works only for linear classification, while we need a non-linear 3 class classification. To overcome the non-linearity issue, we use some advanced techniques like the *Kernel Trick*. This trick allows the algorithm to project data in an higher dimensional space, to shatter the non-linear terms. We used the Radial Basis Kernel (RBF):

$$K(\mathbf{x}, \mathbf{x}') = e^{-\gamma\|\mathbf{x}-\mathbf{x}'\|^2}$$

In order to obtain good results, we also had to set optimized value for two of the kernel parameters:

- γ, that acts like an inverse of the standard deviation, ranging from 2^{-15} to 2^3;
- c, that acts like a regularization term and works for avoid the misclassification occurrences, ranging form 2^{-5} to 2^{15}.

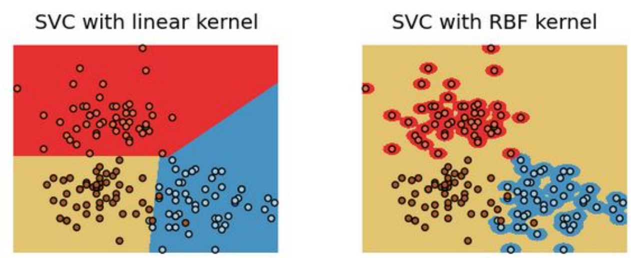

Fig. 6: *Visual representation of the work of two different SVM models. (SVC stands for the implementation of SVM in programming environment). Figure taken from Stackoverflow.*

After tuning the SVM, the classification starts performing an one-vs-one voting strategy, where multiple binary classifiers are trained and used to label a sample: the class that receives the highest number of votes will be the chosen one. This because we perform a $K = 3$ classification, so we need to train $K(K-1)/2$ binary classifiers.
At the end, with a 10×10 cross-validation, data is randomized and divided in 10 folds. Nine of these folder is used for training, while the last one is used for testing [36].

VI. FES

After the feature extraction and the classification is done, we need to use these inputs for actually doing the required movement. Our approach relies on *functional electrical stimulation* (FES) because, through the years, it has been proven to improve multiple body system, such as lower and upper extremity functions and bladder functions [37].
Also, we are supposing the nerves and muscles are not damaged in the patients, the only injury they have is in the spinal cord.
FES is the application of electrical current to tissue that can

be excitable, with the aim to replace lost functions in neurologically impaired individuals. In the last 40 years, methods and principles for modulating the strength of the impulses for the tissue contractions have been well investigated, some systems are already commercialized, but the research is still strong in this field [38]. We consider this methodology robust and reliable, so we are expecting good results from it.
In Figure 7 we show a typical representation of a FES system. In our case the *external control unit* (ECU) is controlled by the classified and labelled signals from the previous section.

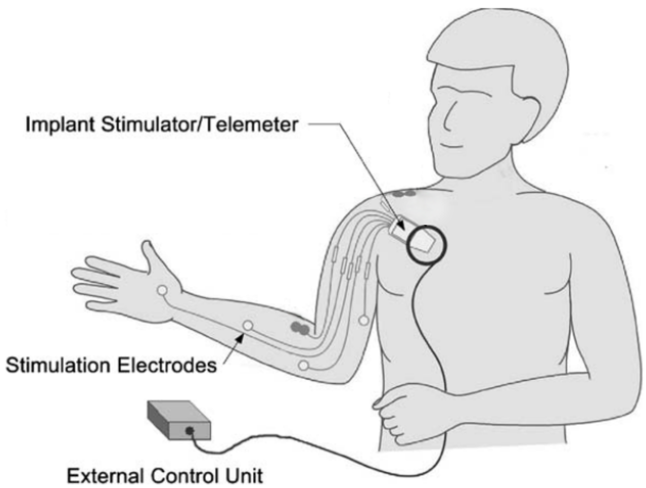

Fig. 7: *Typical representation of a FES system [38].*

A. Our implementation

The input signal arrives in a device working as a switch: it activates different regions based on the classification label.
Following Hoshimiya approach [39], the muscles we want to stimulate are the following:

1) fingers (II-V): FDS, FDP, ED;
2) thumb: EPB, AbPL, AbPB, OpP, FPL, FPB,
3) wrist: ECRL, ECRB, ECU, FCR, FCU;
4) elbow: heads of the triceps and biceps.

In the original experiment, 21 needles were implanted in the mentioned muscles, using spinal needles and coiled wires electrodes; implantable stimulators are common in FES for SCI [40], but requires a professional in the medical field for the needles placement.
We decided to use a percutaneous system during the testing, but a implanted neuroprosthetic system could be designed for a long-term use. Our switch activates fingers, thumb and wrist for an input signal labelled as *grasp* and the elbow for one labelled *reach*. If the signal is labelled *rest*, no action is performed.
We can decide the duration of the action tuning the *pulse duration* and the *stimulus magnitude* of the generated impulses. The graph in Figure 8 can be used as a reference for numerical values.

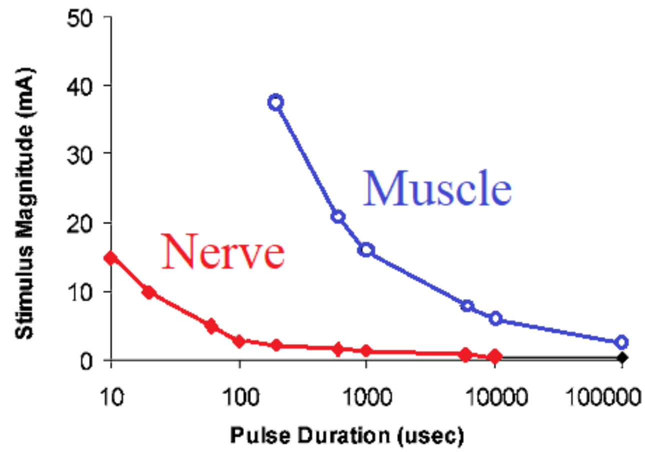

Fig. 8: *Figure modified from [38].*

The third and last fundamental parameter is the *impulse frequency*: if it is too low, the muscle has some twitches and above a certain level it produces a smooth contraction. Typically, the range 12-15 Hz is used, so we use the same range for our system.
Regarding the waveform, we decided to use a biphasic wave, so a wave with a negative phase followed by a positive phase, to avoid the possibility of tissue damage [38].

Abbreviations:
BiLg: Long head of the biceps brachii
BiS: Short head of the biceps brachii
TrLg: Long head of the triceps brachii
TrLt: Lateral head of the triceps brachii
TrMd: Medial head of the triceps brachii
Anc: Anconeus
Br: Brachialis
BrR: Brachioradialis
ECRL: Extensor carpi radialis longus
ECRB: Extensor carpi redialis brevis
ECU: Extensor carpi ulnaris

VII. INTRUSIVE BCI

In the recent years, a new invasive device, called *bridge* has been utilized on SCI patients for their recovery and the results are promising. The device, as the name suggests, works as a bridge between the healthy vertebrae and the rest of the spinal cord, bypassing the injured part. Intraspinal stimulation produces more gradual and natural recruitment of motor units compared to muscles/nerves stimulation [41]. This method has been proved very useful and effective in rats, with almost no need for training after the implant, but it does not have the same results in humans yet. According to Capogrosso et al. [42] this is due to interferences between the *epidural electrical stimulation* EES and the proprioceptive input[2] in humans, but we will talk about how we can cope with this later on.
Our artificial neural connection is meant to work as an

[2]signal that gives the sense of self movement and body position

amplifier and filter for the natural neural activity with the aim of restoring the connection with the lost path. We hope that our brain-controller stimulation could accelerate the recovery of the upper limbs in SCI patients; in Figure 9 the proposed system is shown.

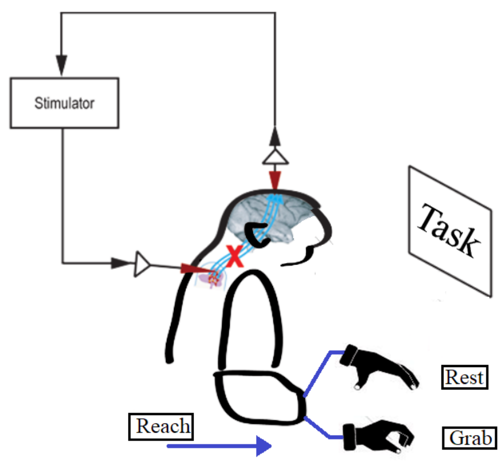

Fig. 9: *Representation of the intrusive system. Figure adapted from [41].*

More in details, the different phases for the implementation are:

1) *Installation.* Obviously surgery is required to implant the electrodes in the spinal cord, but each patient has different injures at different levels. In general, we can say we would follow the same experience of Nishimura et al. [41], placing silver electrode wires of 0.1 mm diameter, 50 kΩ at 1 kHz, after small incision in the dura, wrist and arm area of primary motor cortex and dorsal of premotor cortex. To prevent the sensors from detaching, some screws could be used to fix their position on the skull.
2) *Amplifier.* To check the initial effectiveness of the connection and for the further tuning the of set up, some simple EMG electrodes could be placed on the arm and hand muscles to monitor if there is some activity. The bridge can then be set to amplify more or less the original signals. Then, the amplitude should be fixed and the patient should be able, with some training, to adjust his/her activity for the task.
3) *Proprioceptive feedback.* As mentioned before, this is a recent issue, theorized in 2018 [42], and even if studied only for locomotion, we believe we should take some precautions too. The problem is the probability of collisions of proprioceptive afferents during EES, which is blocking the propagation of naturally generated proprioceptive signals to the spinal cord and the brain. This is very common in human when compared to rats. This probability depends on EES frequency and firing rate. The information delivered by proprioceptive organs is related to the limb velocity, movement, carried load. It

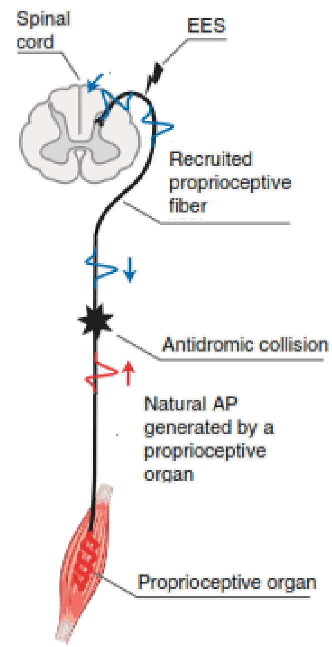

Fig. 10: *Figure modified from [42].*

is distributed along the spinal cord that directly activate motor neurons. To preserve the natural proprioceptive signals, a stimulation protocol should be implemented. In particular,

- the EES should be burst with high frequency and low amplitude;
- the EES have to be burst over spacial selective spinal cord regions. This can be done using a temporal sequence; it has to coincide with the firing profile of the prorioceptive afferents in the specific spinal cord region analysed.

4) *The BCI.* The bridge is not always ”open”, letting the signals through, but we need to decide when the signal has to pass to induce the desired movement. The same BCI implemented in the previous sections is used to detect the features. Then, when any kind of feature is detected, the bridge does not suppress the signal anymore and the electric signal is free to stimulate the naturally designed muscles.

Observations:

- in some cases, even with a severe lesion on the spinal cord, some weak ECG activity could be registered. In this case the proposed methodology can be used to boost the muscles activity.
- In rats, BCI mediated stimulation is clearly better [43] than continuous stimulation, this is why we prefer this approach in our implementation too.

The results should be good and observable after a short time for what concerns the arm flexion and extension , the grasping movement would probably take more training before reaching acceptable developments.

VIII. Conclusions

In this paper we talk about SCI problems and how a BCI can improve the quality of life of these patients. We propose our own methodology and possible system. In particular we use MI to train the patients in order to restore abnormal brain patterns that are present along with a SCI. This training is done before the actual tuning of the BCI system and we hope it could help to achieve a better feature extraction, but also to make it faster. MI is also used in the BCI system, where the extracted features are classified using a SVM. We proposed both an invasive and a non-invasive solution for restoring the movement, using the labelled features: the non-invasive solution is based on a well known and widely studied approach called FES; the invasive solution exploits the *bridge* technology, which is a more recent approach and, nevertheless, a promising one.

From our work we expect to have an improvement with respect to the currently implementations, that we would like to achieve using the MI training, which represents a novel approach in the field. For what concerns the BCI system, we expect to achieve results in line with the current literature, as we exploit quite standard and robust approaches.

Regarding possible future enhancements to our system, we may cite a better pipeline in the MI training, based on experience gained during this first study; we expect to develop a more personalized and patient-based approach, both in the MI training and in the BCI setup. In future works we would also establish if a different classifier performs better, in particular the LDA and LR ones, which are commonly used in BCIs. Also the use of multiple different classifiers at the same time could improve the performances and may be studied for our work.

In conclusion, as this is just a theoretical work, the natural evolution of the proposed system is the actual development of the the real BCI and the starting of trial session with patients. Up to now we expect promising results and we hope to even improve them in the future.

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