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Haptic Stimulation for Improving Training of a Motor Imagery BCI Developed for a Hand-Exoskeleton in Rehabilitation

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Abstract— **The use of robotic devices to provide active motor support and sensory feedback of ongoing motor intention, by means of a Brain Computer Interface (BCI), has received growing support by recent literature, with particular focus on neurorehabilitation therapies. At the same time, performance in the use of the BCI has become a more critical factor, since it directly influences congruency and consistency of the provided sensory feedback. As motor imagery is the mental simulation of a given movement without depending on residual function, training of patients in the use of motor imagery BCI can be extended beyond each rehabilitation session, and practiced by using simpler devices than rehabilitation robots available in the hospital. In this work, we investigated the use of haptic stimulation provided by vibrating electromagnetic motors to enhance BCI system training. The BCI is based on motor imagery of hand grasping and designed to operate a hand exoskeleton. We investigated whether haptic stimulation at fingerpads proves to be more effective than stimulation at wrist, already experimented in literature, due to the higher density of mechano-receptors. Our results did not show significant differences between the two body locations in BCI performance, yet a wider and more stable event-relateddesynchronization appeared for the finger-located stimulation. Future investigations will put in relation training with haptic feedback at fingerpads with BCI performance using the handexoskeleton, in grasping tasks that naturally involve haptic feedback at fingerpads.**

I. INTRODUCTION

Brain-computer-interface (BCI) creates a communication channel between a person and an external, non-biological device by analysing only brain signals, thus regardless of any activity of the peripheral nervous system and muscular system.

The original intent of BCI development was mainly to restore a basic communication channel between a locked-in or a severely paralyzed patient and the outside world. Still over the years BCI systems have been proposed for mental control of different devices, from wheelchairs to prosthetic limbs. Certain typologies of BCIs, those based on motor imagery (MI), are particularly suitable for restoring a natural motor control pathway in patients affected by neuro-motor disorders. In fact, MI - BCI can be used as a valid replacement for active motor training as it can detect features of brain activity (Event - Related - Desynchronization, ERD) that are directly correlated with the motor intention of the paretic limb [1]. Thus it is possible, by means of robotic rehabilitation devices driven by the BCI, to influence motor recovery in a positive way by providing motor assistance to patients congruently with the detected active motor intention involving the paretic limb [2]–[5]. The use of sensory feedback in MI-BCI systems has the double-fold advantage to both improve the performances of the BCI itself and to close the sensorimotor feedback loop [6], [7]. There is now sufficient evidence in stroke rehabilitation that non-invasive BCI can offer an advantage in patients with severe motor impairment compared to traditional rehabilitation methods [7]–[11]. Then, performance of the BCI becomes a critical factor, since it directly influences congruency of the motor feedback provided to patients. Performance in the use of BCI can be improved by training, and both mental activity of the human subjects and parameters of the BCI can adapt each other during training. Wide research interest has been provided in investigating the effect of different sensory feedback in BCI training and final performance. In [12] vibrotactile feedback has been proposed for training a three class BCI with reasonably good accuracy. In [13] proprioceptive feedback provided by a robotic hand orthosis showed a clear enhancement in ERD detectable by the BCI. In [14], [15] illusory movements elicited by tendon vibration at about 70 Hz showed increased BCI performance with respect to visual feedback only. In [16] authors demonstrated that vibrotactile stimulation is particularly effective using stimuli based on a 175 Hz sinusoidal carrier-wave modulated by a 27 Hz wave: with these frequencies two types of mechanical receptors were intended to be stimulated: Corpuscles of pacini, susceptible to frequencies above 100

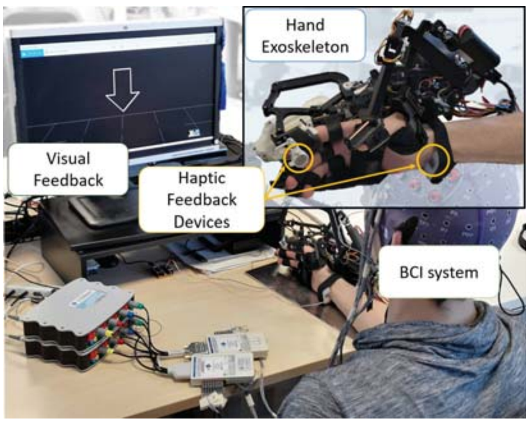

Fig. 1. Experimental setup

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Hz, and corpuscles of Meissner, susceptible to frequencies ranging from 20 to 50 Hz.

In further studies conducted in [17] and [18], it was shown that the use of tactile selective attention during motor imagery tasks increased the performance of a BCI system, improving accuracy in stroke patients. In these works, body location of the vibrotactile stimulation is different, the wrist for the first works and the finger for the latter. In a recent study [19], it has been shown how a continuous kinaesthetic feedback (tendon vibration applied at the level of the elbow), coupled with a visual feedback, significantly increases the BCI correct rate in respect to the visual only feedback. Moreover, the authors documented a better performance in the group trained using the multisensory feedback (kinaesthetic plus visual) with respect to the group trained using the visual only feedback. Analogously, in a study involving eleven stroke patients [20], it has been proven that the presence of a tactile stimulation (applied at the wrist) significantly improve the decoding accuracy of the BCI system.

In this work we investigate differences in the BCI performance depending on the location of the vibrotactile stimuli. The objective is to evaluate, and possibly further improve, the most effective method to provide vibrotactile haptic feedback for enhancing BCI training. Importantly, the BCI adopted in this study has been developed for assisting grasping through a novel hand exoskeleton developed by our laboratory [21] and experimented both in neuro-rehabilitation [22] and myoelectric control [23]. The introduction of the haptic feedback coupled with the BCI-based robotic rehabilitation, would allow to reduce the training time and thus to have more effective rehabilitation sessions.

In this work we investigate whether vibrotactile haptic stimulation at fingerpads proves to be more effective than stimulation at wrist, already experimented in literature.

It is known that there is a higher density of mechanoreceptors at the level of the fingers (physiological analysis demonstrated that both Pacini and Meissner corpuscles are substantially more dense at fingertips), therefore we hypothesize that vibrotactile haptic stimulation at fingerpads could be more effective than the same stimulation at the level of the wrist in terms of MI-BCI performance.

II. Experimental Setup

The experimental setup consisted of an EEG acquisition system, two haptic devices for providing tactile stimuli and a hand exoskeleton for providing the motor output once the motor intention is detected by the BCI system. In Figure 1 the experimental setup is shown.

A. EEG Acquisition System

The acquisition system used to extract brain activity consists of a group of devices developed by g.tec "Guger Technologies" including a cap with active electrodes, a signal conditioner ("g.GAMMAsys") and an amplifier with digital conversion of the measured signals ("g.USBamp").

A total of twenty-three electrodes were used and placed according to the 10-20 standard, of which twenty-one were localized in the sensorimotor zone and two located in the frontal area close to the eyes (see Figure 2). Active electrodes were used with conductive gel between the electrodes and the skin, in order to improve electrical conductivity. The ground electrode was placed in the frontal area (AFz channel) and the reference electrode at the left earlobe. Signals were pre-filtered in the 2-30 Hz frequency band (bank filter embedded in the g.USBamp) and then digitally converted with sample frequency of 256 Hz and resolution of 24 bits.

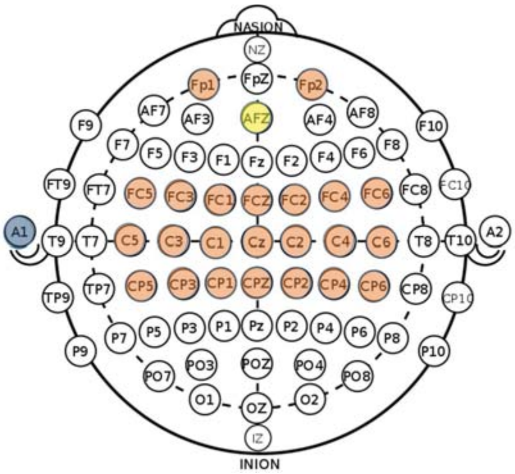

Fig. 2. electrodes placement according to the 10-20 standard configuration.

B. Haptic Devices for Vibrotactile Feedback

A fingertip haptic device and a haptic bracelet were used to render vibrotactile stimuli at the two locations of the body investigated in this study: fingerpad and wrist. The adopted fingertip haptic device is the Haptic Thimble [24]. It is a wearable lightweight haptic device designed to be worn specifically on the user's last finger phalanx. An electromagnetic actuator, embedded in the thimble, actuates a flat tactor to provide the user's fingerpad with tactile stimuli in a wide frequency range.

The haptic bracelet was custom realized by embedding an electromagnetic actuator in a commercial bracelet in order to properly place the actuator on the user's forearm. The electromagnetic actuator used for the wrist is the same of the one embedded into the Haptic Thimble. Such electromagnetic actuator is able to generate vibratory stimuli in a wide bandwidth range ($0 - 350 Hz$). In this work both actuators were driven by a 175 Hz carrier wave with a 27 Hz modulation wave (as in [17]). Moreover, independent control of both amplitude and frequency of the generated stimuli is allowed. The thorough characterization of the actuator can be found in [24].

C. Hand Exoskeleton

In order to resemble a clinical environment a hand orthosis was included in this study and its movement was controlled by the BCI output. The hand-exoskeleton used in the experiment had been formerly used for the development of a bilateral rehabilitation of hand grasping protocol [25]. The device, thanks to the five independent underactuated parallel kinematic chains, is able to guide the opening and closure motion of the user's hand. When worn, the hand-exoskeleton is stably connected to the back of the user's hand by means of velcro stripes, whereas, at the user's fingers level, the device is featured by connections able to exert only forces normal to the user phalanges achieving a high level of effectiveness and comfort as described in both [21] and [26] where the development of finger-exos and thumb-exos are respectively described. As reported in Figure 1, the hand-exoskeleton was grounded on the desk in order to compensate the device weight. The hand-exoskeleton, together with the BCI system the presented study is targeted to, represents the core of the envisaged neuro-rehabilitation system for hand grasping training. In this study the hand-exoskeleton was used to provide feedback of hand closing and opening.

III. Experimental Methods

The experiment involved 11 healthy subjects (four females, seven males, all right handed, average age 27 ± 3 years), all of which were BCI naive subjects; this study was approved by the Sant' Anna School of Advanced Studies Ethics Committee, Pisa, Italy. Before attending, all participants signed an informed consent form.

A. Experimental Protocol

The subject was invited to seat in front of a desktop, 70 cm in front of a monitor, to wear both the hand-exoskeleton and the haptic devices (described in the next sections). The position of each subject was fine adjusted in order to make him/her feel comfortable and relax the muscles, so as not to create detectable movement artifacts. The hand exoskeleton was placed on the desk and held in position by a static support to avoid changes while performing the experiment due to exoskeleton movements. Then, the subject was helped to wear the eeg-cap and electrolyte gel was applied to the electrodes.

Each subject underwent five consecutive sessions lasting about 7 minutes each (see Figure 4). The first session,

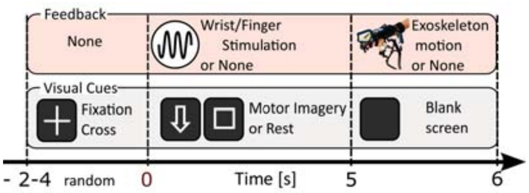

Fig. 3. Scheme of the experimental protocol

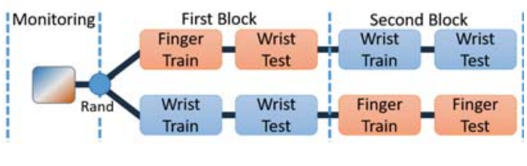

Fig. 4. Graphic representation of the trial structure.

called Monitoring session, was used to allow the subjects get familiar with the haptic stimulation. A total of 20 stimulations for the wrist and 20 stimulations for the finger, lasting 5 seconds each and randomly ordered, were provided to the subjects accordingly to the trial structure of Figure 3. Subjects were requested to maintain a relaxed mental state during the Monitoring session. The subsequent 4 sessions were divided in two blocks containing a train and a test session each (see Figure 4). The two blocks differed by the location of the haptic stimulation: the Wrist block and the Finger block. Each session contained 40 trials lasting eight seconds and a random interval of 2 to 4 seconds spaced from the next one (see Figure 3). Each task was triggered in the LCD screen with visual indications. A visual cue indicated the subjects which task to carry out: an arrow pointing downwards indicated to carry out the motor imagery of the right hand ("move" class), and a square indicated to hold a resting mental state ("rest" class). The order of the 20 "rest" trials and the 20 "move" trials was generated randomly at the beginning of each session. The Train sessions were used to determine the parameters of the BCI to drive the following Test sessions. In the Train sessions the haptic stimulation (in the Wrist or the Finger accordingly to the block session) was provided to the subjects during the active period (from second 0 to second 5 of Figure 3) of the "move" trials followed by the movement of the hand exoskeleton lasting 1 second. In the Test sessions, the haptic stimulation was driven by the BCI output in real time. In particular, the BCI detection of the "move" class made the haptic stimulation activate. On the other hand, when the "rest" class was detected, the haptic stimulation kept being deactivated. On the other hand, during the detection of the "rest" class, the haptic stimulation kept being deactivated. The hand-exoskeleton movement, introduced in the experimental protocol in order to resemble a clinical environment, was provided to the subjects for 1 second (in the time period from 5s to 6s in Figure 3) only when the BCI detected the "move" class for one cumulative second in the time period ranging from 2 to 4 seconds.

During the Finger block only the haptic device placed at the fingertip was active, whereas during the Wrist block only the haptic device placed at the wrist was active. The presentation order of the Finger block and the Wrist block was randomized across subjects.

B. Data Analysis

The two mental states ("rest" and "move") were decoded using the Common Spatial Filter (CSP) approach [27]. The first stage of this approach was the CSP linear supervised Spatial filtering that found directions for maximizing variance for one condition while minimizing variance for the other (i.e., "rest" and "move").

The 8 - 30 Hz band - power log variance was then calculated for the first and last two CSP - projected channels and a Support Vector Machine (SVM) linear classifier was trained to calculate the distance between the "rest" and "move" classes of the extracted characteristics from the classification threshold. The weights of the spatial filter

(CSP) and the weights of the linear classifier (SVM) were therefore extracted to be used in the subsequent test for each training session.

The BCI performance then consisted of the real - time BCI output obtained in the test sessions with the parameters of the BCI tuned on the corresponding train sessions. The correct classification rate was calculated by transforming the BCI output into a binary signal assuming values equivalent to zero and one respectively for incorrect and correct classification. In the time range between 2 and 4 seconds of each trial, the correct classification rate was calculated as the average of the binary signal obtained and used in the following statistical analysis. Using the EEGLAB software [28], EEG data processing (epoching, denoising and time - frequency transformation) was carried out.

Time-frequency analysis with the baseline permutation statistical method for inference testing [29] was calculated using the full - epoch length single-trial correction method. In particular, 500 permutations with a p - value of 0.05 were used at each frequency and the additive ERSP model was assumed (results are shown as z-scores in Figure 5). The time baseline for normalization was selected as 1.5 seconds before the beginning of the visual cue. The decomposition of the time-frequency was performed using a Morlet wavelet with a 1 second moving window. The number of cycles in each Morlet wavelet increased linearly with frequency using 3 cycles at lowest frequency to 30 at highest estimating 27 linear-spaced frequencies from 3.0 Hz to 30.0 Hz.

IV. Results

Results shown in Figure 5 focus on EEG correlates of the motor imagery activity performed in the two experimental conditions, namely finger stimulation (F) and wrist stimulation (W). Measurements are averaged over motor imagery trials and over subjects. The horizontal axis reports the time

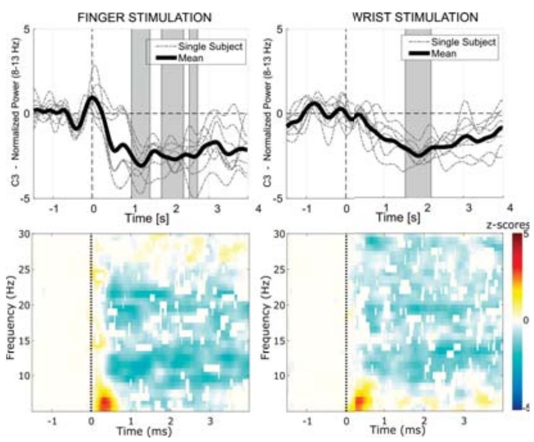

Fig. 5. Comparison of the EEG correlates of the subjects in the two experimental conditions Finger stimulation (left column) and Wrist stimulation (right column). First row: 8-13 Hz band-power desynchronization on the C3 electrode (covering the right hand area in the primary motor cortex), significant area are gray-highlighted; Second Row: Time-frequency contributions averaged over “move” trials, subjects and electrodes (only significant values are colored).

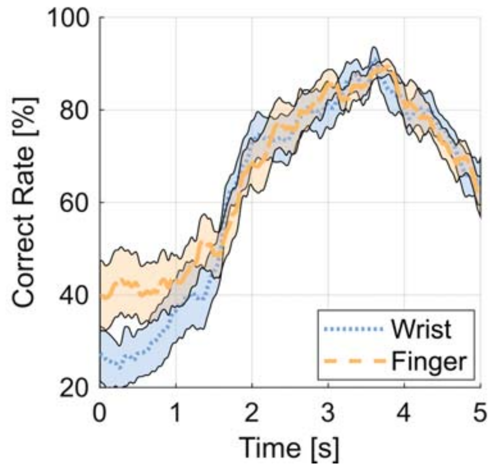

Fig. 6. Classification performance over time averaged over subjects and trials in the two experimental conditions.

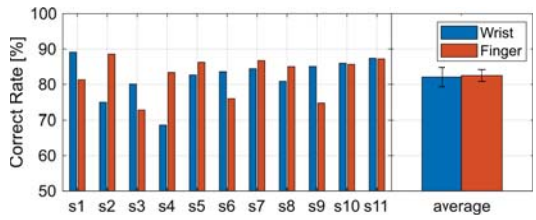

Fig. 7. Correct rate obtained by each of the eleven subject in the two test conditions (Wrist and Finger stimulation). On the right the correct rate averaged over subjects.

in seconds of the trial and the dotted line indicates the start of the trial (“Move” visual cue shown to subjects). Top graphs in Figure 5 report the measured band-power in the 8-13Hz band: as expected, after about 1 s after the start of the trial, a significant ERD is noticeable for both conditions. In particular, the F condition shows a more stable ERD over a wider period of time (solid gray areas highlight a statistically significant ERD over the trials). The cumulative time-period showing significant ERD was $1.2s$ for the F condition and $0.8s$ for the W condition. Time-frequency plots (bottom graphs in Figure 5) show also a deeper ERD in a broader frequency band with respect to the considered mu-band (8-13 Hz) in the F condition. Beta band (16-24 Hz) appears also more involved in the ERD generated in the F condition than in the W, especially during the first half of the trial.

Final performance measurements of the BCI classifier (reported in Figure 7) did not evidence a significant difference between the conditions. Although for the F condition the average performance was slightly higher and with less variance between subjects, the difference was not statistically significant.

Graph in Figure 6 shows the correct classification rate computed throughout the trial period and averaged for the “Move” trials only. The mid period of the trial evidences the highest classification rate for both conditions, according to the graph shown in Figure 5 where stable ERD was evidenced in the mid part of the trial period. Similarly to the averaged results, there are no noticeable differences between the classification performances over time obtained in the two experimental conditions.

V. Discussion

As reported in [20], when applied while performing motor imaging tasks, vibrotactile stimulation increases the classification performance of a motor - imagery based BCI system. In the study the vibrotactile stimulus was applied at the wrist, yet we know from physiological knowledge that Pacini and Meissner corpuscles, stimulated by the vibration, are present in greater number in the fingerpad area. We expected that a higher density of mechanoreceptors could increase intensity and stability of brainwave-correlates (i.e. the Event-Related-Desynchronization) of these sensory afferents, and in turn improve classification performance of a BCI based on extraction and classification of these features. We started from this point, analyzing in this study if there are significant differences in BCI performance between the application of the vibrotactile stimulus at the wrist or at the fingerpad. Although results regarding the analysis of the EEG correlates (Figure 5) suggested more stable features related to ERD for the F condition, these improvements were not sufficient to result in a significant improvement of the final BCI classification performance (an average correct rate equal to $82.2 \pm 3\%$ for the F condition and $82.7 \pm 2\%$ for the W condition). This aspect may be partly related to the fact that Pacini corpuscles are very sensitive to remote stimulation [30], and thus the density of the receptors may be not a crucial factor for the BCI perfromance. It will be of interest, in future work, to test whether the training conducted with feedback at the fingerpad can result in significant better improvements when using the hand exoskeleton driven by the BCI in the final rehabilitation setting, since feedback at the fingerpad is also closer to the natural feedback perceived during grasping.

VI. Conclusions

In this work we investigated vibrotactile stimulation as a method to improve training in the use of a motor imagery BCI system. In particular, we focused on a BCI based on motor imagery developed for operation of a hand-exoskeleton in neuro-rehabilitation training of hand grasping. In such rehabilitation scenario, congruency between motor intention of the patient and the sensory feedback provided by the exoskeleton is crucial in order to promote a normal reorganization of brain plasticity. It results that performance of the BCI used during rehabilitation sessions in the hospital is a very important aspect to consider, and methods able to increase such performance, even through additional training sessions at home, can be valuable. The use of vibrotactile haptic feedback has shown to be a viable method to improve BCI training through relatively simple devices. In this study we investigated whether the effectiveness of this method can be further enhanced by changing the point of application of the vibrotactile stimuli, according to the expectation that higher density of mehcano-receptors would lead to more evident EEG correlates of the somato-sensory afferent. We experimentally compared two locations of the body, the wrist and the fingerpad, for providing vibrotactile feedback during training of a BCI based on motor imagery of hand grasping. From the data obtained, we can confirm that the use of a vibrotactile stimulus according to the specifications lead to high accuracy in the control of the BCI system; we have also shown that the point of application of the vibration is not indicative of the obtained correct rates. Final results did not show significant differences between the two body locations in BCI performance, still a wider and more stable event-related-desynchronization appeared for the finger-located stimulation. Interesting further investigations will be addressed in correlating training with haptic feedback at finger-pads with the final online BCI performance using the hand-exoskeleton. The use of the hand-exoskeleton is devised for the neuro-rehabilitation treatment at the hospital, since it provides to the patient the most natural afferent feedback with respect to the hand motor functions to be trained. Yet vibrotactile feedback represents a convenient method to perform BCI training, that can be practiced beyond the limited time period of rehabilitation sessions at the hospital, and without availability of the more complex rehabilitation robotic devices.

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