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A fMRI study of the Cross-Modal Interaction in the Brain with an Adaptable EMG Prosthetic Hand with Biofeedback

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Abstract— **Mutual adaptation between man and machine is necessary for the development of more efficient devices that allows easy adaptation. The interaction with intelligent machines involves adaptation processes from both the user and the machine. The human body has the ability to change its body schema to include external tools in it, using this fact we proposed the design of intelligent machines with biofeedback to the user, permitting in this way, development of subconscious control of external devices. We propose the case of an EMG prosthetic hand with biofeedback to study the adaptation process between man-machine. Our system includes an EMG classification system to acquire the intended movement from the user. We use electrical stimulation as a provider of tactile feedback, to interact with the human body. We use a functional Magnetic Resonance Image study while using the prosthetic device while receiving biofeedback to measure the activation levels in the amputee's brain.**

I. INTRODUCTION

The mutual adaptation between man-machine opens new possibilities in the development of better user friendly interfaces that not only adapt to the user's characteristics, but also, permits the adaptation of the user to the machine. There are several examples of the use of feedback to improve the man-machine interface. One example is the use of sound to acquire cues in the interaction with the machine [1]. These studies show the improvement in the interaction when we increase the number of communication channels between the man and the machine. The problem with sound cues is that need the conscious effort to be recognized. Hunter et al. [2] shows another example of the importance of increasing the communication channels. In this study they show how the multiple sensory stimuli contribute to the conscious awareness of the body, and how it can be used to change the abnormal body awareness that occurs after limb amputation. This effect is also known as cortical reorganization where the brain after losing the stimuli from the amputated limb, due to the cross-modality, received input signals from the adjacent neurons, resulting in what is called "phantom limb".

With the proper stimuli combination, the body image can be change, allowing for the human body to adapt to external devices. In order to test this hypothesis we proposed the used of an adaptable EMG controlled prosthetic hand with tactile feedback using electrical stimulation. Lotze et al [3] showed the positive effects in the use of myoelectrical prosthesis to revert cortical reorganization. Giraux et al. [4] also shows the possibility to revert cortical reorganization in the brain. This is possible due to the combination of the intentionality from the amputee to move the absent limb, which results in muscular movement, and the visual feedback provided by the myoelectric device. We think that if we include even more sensory channels, in this case, tactile feedback, the adaptation to the prosthetic device can be enhanced, resulting in subconscious control of the device.

The development of myoelectric prosthetic hands has advanced incredibly since their introduction in 1960 [5]. The myoelectrically controlled devices are preferred over the body powered ones because the latest are restricted in their area of application, and the cosmetic ones do not provide any advantage to their user on his activities [6]. Still, one mayor drawback of the EMG controlled devices is the minimal or nonexistent biofeedback, that is, information on the status of the prosthetic device, hand or leg, to the body. Our body is a multimodal system that uses several channels to obtain the current status of our bodies, if one channel fails; there are still others that help to provide the missing data. The user of a prosthetic hand needs to overcome the lack of tactile and proprioceptive data with visual feedback, which causes to fatigue faster because of the increment of conscious effort to control the hand [7]. These mechanisms need the implementation of a feedback source that enables the user to develop extended physiological proprioception [8]. We find some examples in the application of "tactile feedback" using vibration [9] or electrical stimulation [10]. On the hand, in the man-machine interfaces studies we find haptic interfaces that provide tactile feedback. Their direct application to prosthetics is limited due to the fact that all these researches focus on the sensorial substitution using the finger tips [12]. Regrettably, those cannot be applied to prosthetic devices where the user presents partial or complete loss of the arm, which are our interest in this study. Therefore, we need to find a different way to provide with sensorial information to the human body. It is been demonstrated that the brain works with correlative information, therefore when provided with simultaneous stimuli, the brain can associate the stimuli into a

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unique event [12]. Using this knowledge, we can force the brain into produce new sensations, provided that the stimulus is simultaneous, so the person using a prosthetic hand can have sensorial feedback besides the visual.

II. MATERIALS AND METHODOLOGY

The prosthetic system in our laboratory uses an adaptive discrimination method to classify the human intention using the EMG signal from three sensors placed on the forearm of the user. There are several methods to provide the prosthesis to the human body that can be divided in invasive and non invasive. We focus our research in the non-invasive method. This method does not interact directly with the natural pathways, but is easier to develop, does not require complex surgical interventions, and the rejection from the body is minimal. In this study we use transcutaneous electrical stimulation, which also can be applied during the scanning inside the functional magnetic resonation imaging chamber.

The use of visual or auditory feedback only is not reliable enough to provide with sensory feedback for proper subconscious control of the artificial limb. In order to solve this drawback, we need to provide with tactile information, that is, a way for the body to interact directly with the environment. In previous studies, the electrical stimulation has been used to provide an on-off signal as sensory feedback, with promising results, but lack of more objective system evaluation. The participants to these experiments shows an improvement in their use of the prosthetic device, and even voice the opinion of "feeling" the robot hand more as part of their bodies. Although these studies present promising results, we still need to understand more the relationship between the man and the machine for better future applications.

One of the drawbacks of using electrical stimulation is the "noise" generated by it. This noise can affect the discrimination of the EMG signals. We need to implement a system that, while providing the necessary feedback, does not affect the discrimination of the user's intention.

We transmit the tactile information from the prosthetic hand to the body using a transcutaneous electrical stimulator developed in our laboratory that works as a transducer between the forces applied over the pressure sensors installed on the finger tips and the palm of the robot hand and the biphasic square signal applied to the body. The transcutaneous stimulator device used in this study was built using a Renesas tiny H8 3664 microprocessor. We produce the stimulation signal using the PWM port of the microcontroller. The device is controlled by receiving the control commands from the computer using serial communication at 19,200 Bauds. The voltage output is set at 9Volts. This device uses the biphasic stimulation method, because it requires of less energy to provide with the same effects of other stimulations, keeping the flowing current at a low level (10mA). We regulate the intensity of the stimulation by changing simultaneously the duty rate of both positive and negative phases, while keeping the pulse frequency constant

A. Experimental Setting

Using the prosthetic system described above, we perform a series of experiments to measure the activation on the region SI of the brain to see the effects of the electrical stimulation when its works as biofeedback for the myoelectric prosthetic hand. In order to measure the effects we first evaluated the response of the body to the stimulation alone as an unrelated event. Following, we measure the brain activation to the electrical stimulation when is applied as a result of the robot hand touching and object, working along with the intention from the body and the visual feedback.

As stated above, we regulate the stimulation by changing the duty rate of the signal, thus, any reference to the intensity in the stimulation will be stated according to the percentage of the duty ratio. The neural transcutaneous electrodes were placed on the upper left arm. This is done in order to avoid the insertion of electrical noise due to the electrical stimulation. The distance between electrodes was set to 1 cm. Our control group consisted of two healthy men in their 20's, who do not present any visible physical alteration. We placed the sensors similarly to the amputee.

Our test subject for this experiment is a right arm amputee woman in her 50's. The amputation was performed 5 years previously to this study. The amputation was performed over the wrist level, leaving most part of the forearm intact. The surface EMG sensors were placed over the right forearm, bellow the elbow joint as shown for the pattern classification process. For this experiment, we trained the classifier with the following motions: fingers flexion/extension, wrist flexion/extension, thumb flexion.

In order to provide with visual feedback, we used a video camera to show the subjects the prosthetic hand movements while inside the fMRI device. The subjects see the image through a set of mirrors that allow transmit the image from the video camera (Fig. 1). This is necessary because the fMRI does not allow the inclusion of the robot hand inside the room, due to the strong magnetic force produced by it.

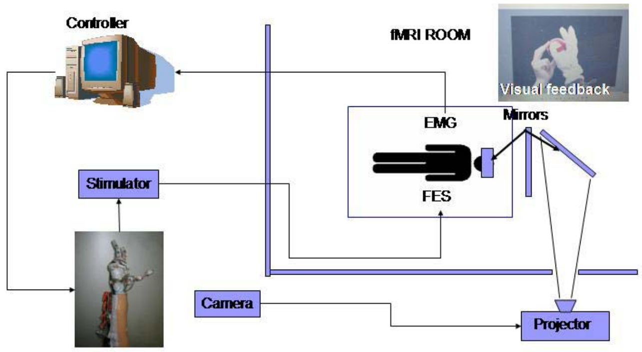

FIG. 1 Experimental setup. The subject lies inside the fMRI device with the EMG sensors on the right hand amd the neurostimulation electrodes on the left arm. The visual feedback is provided by an array of mirrors that shows the image of the prosthetic hand inside the fMRI device,

Cerebral activity was measured with fMRI using blood oxygen level-dependent contrast. After automatic shimming, a time course series of 59 volumes was obtained using single-shot gradient-refocused echo-planar imaging (TR =

4000 msec, TE = 60 msec, flip angle = 90 degree, inter-scan interval 8 sec, in-plane resolution 3.44 x 3.44 mm, FOV = 22 cm, contiguous 4-mm slices to cover the entire brain) with a 1.5T MAGNETOM Vision plus MR scanner (Siemens, Erlangen, Germany) using the standard head coil. Head motion was minimized by placing tight but comfortable foam padding around the subject's head. The first five volumes of each fMRI scan were discarded because of non-steady magnetization, with the remaining 54 volumes used for the analysis.

The fMRI protocol was a block design with one epoch of the task conditions and the rest condition. Each epoch lasted 24 seconds equivalent to 3 whole-brain fMRI volume acquisitions. Data were analyzed with Statistical Parametric Mapping software 2000 [20]. The functional magnetic resonance test was set to 8 seconds, with a scan time of 3 seconds, and a rest time of 5 seconds between scan. 54 scans were acquired for each test. The scans were realigned and transformed to the standard stereotactic space of Talairach using an EPI template. Data were then smoothed in a spatial domain (full width at half-maxim = 8 x 8 x 8 mm) to improve the signal to noise ratio. After specifying the appropriate design matrix, delayed box-car function as a reference waveform, the condition, slow hemodynamic fluctuation unrelated to the task and subject effects were estimated according to a general linear model taking temporal smoothness into account. Global normalization was performed with proportional scaling. To test hypotheses about regionally specific condition effects, the estimates were compared by means of linear contrasts of each rest and task period. The resulting set of voxel values for each contrast constituted a statistical parametric map of the t statistic SPM {t}. For analysis of the each session, voxels and clusters of significant voxels were given a threshold of $P < 0.005$, not corrected for multiple comparisons.

B. *Experimental Procedure*

For the experiment related to the hand movement with biofeedback, first, we configured the EMG motion classifier [18] for the subject, that is, we trained the neural network to match the EMG signals for each participant and its corresponding motion in the robot hand. In particular, for this experiment we used the fingers flexion/extension motion to grab a sphere using the robot hand.

The subject was requested to grab the sphere as soon as she sees it approached the prosthetic hand in the image produce by the camera inside the fMRI room. When grabbing the sphere the pressure sensors placed on the hand were activated, and its pressure signal translated into the transcutaneous electrical stimulation signal of 44% to ensure that the test subjects perceived the stimulation while inside during the scan acquisition process. We took three fMRI scans, with a month between each scan. During this time the amputee was requested to practice at home with the same set of hand actions using both the EMG classifier and the transcutaneous stimulation.

I. RESULTS

For the fMRI data analysis we used a value of p=0.005 (spm2), resulting in a threshold value of 2.59. Figure 2 shows the evolution of the cortical reorganization and functional specialization in the amputee's brain due to the myoelectric prosthesis along with the application of electrical stimulation. Our results show a smaller area of activation in the motor cortex when using the electrical stimulation, compared with the activation obtained when having visual feedback only.

The amputee subject presented activation of the frontal lobe, for the application of electrical stimulation at 44% on the left arm (healthy arm). The fMRI analysis shows that the electrical stimulation is not detected on the somatosensory area S1 (Fig. 3), but is spread on the parietal lobe, in charge of the somatosensory information processing. The test shows that the test subject presents some cortical reorganization.

For the amputee, when grasping the cylinder using the robot hand, the activation in the amputee brain increased along the primary motor cortex (M1) related to the right hand. When asked, this person affirmed that there is still the image of the right hand, which is what she used in order to control the prosthetic hand. Figure 4 shows an increase in the activation in the primary somatosensory area (S1), principally in the area related to the hand, but also, we see the activation on the area related on the left arm, where the stimulation is actually performed. After the fMRI scanning, the subjects were questioned on the sensation perceived during the grasping task. The illusion of feeling as if the right hand were touching the object is found in most of the cases.

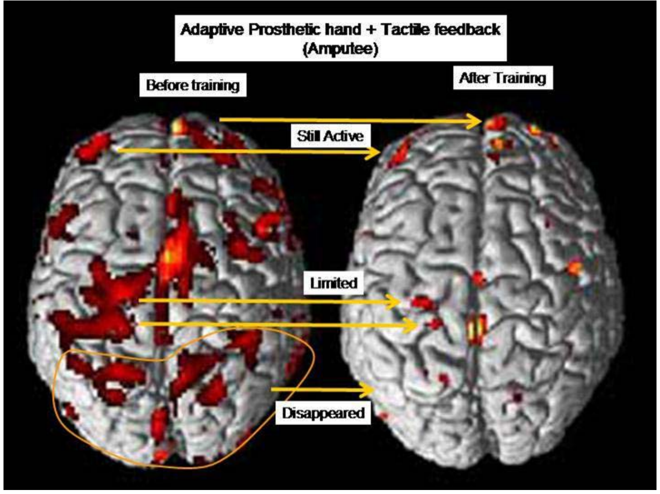

Fig. 2 Shows the evolution on the amputees brain after the 3 months training period of using the EMG prosthetic hand with biofeedback. At the beginning of the experiment (Left) the activation of the brain was spread, showing little specialization of function. This might be caused by the cortical reorganization on the amputee's brain. After the training period (Right), the activation in the brain presents a more function specific activation.

II. DISCUSSION

Corroborating the findings in neuroscience, the brain does react to the application of electrical stimulation (activation of the frontal lobe), but the activation on the somatosensory region of the left arm is not high enough to appear in the fMRI image. Therefore, the electrical stimulation alone does not produce an activation of the primary somatosensory area (S1), the area in charge of the processing of sensation in the specific parts of our bodies. When the stimulation is applied in concordance with the action of grabbing an object, we have three channels working altogether, the intention from the subject, the visual feedback, and the stimulus provided by the electrical stimulation. This action is done several times during the scanning process (8 min), which allows the brain to correlate this information as a simultaneous and repetitive event. The fMRI resulting shows how the brain changes the perception of the electrical stimulation applied on the left arm. Now, the primary somatosensory area (S1) related to the hand presents an activation high enough to be detected in the fMRI image.

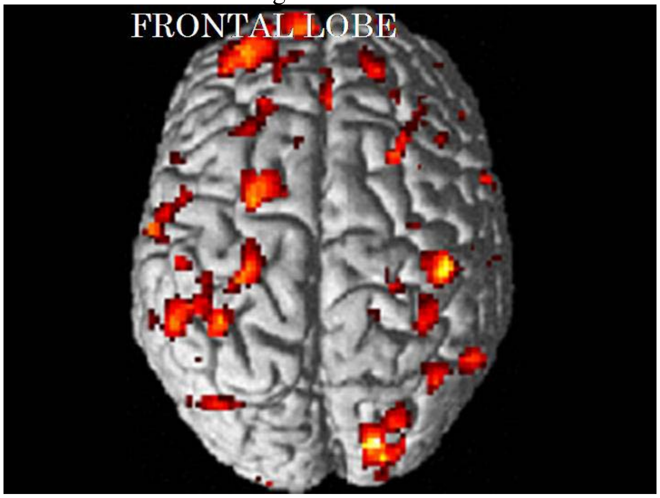

FIG. 3 Shows the fMRI resulting after applying the transcutaneous electrical stimulation on the left arm for the amputee. It is important to notice the activation on the frontal lobe, which identifies the stimulation as new information for the body.

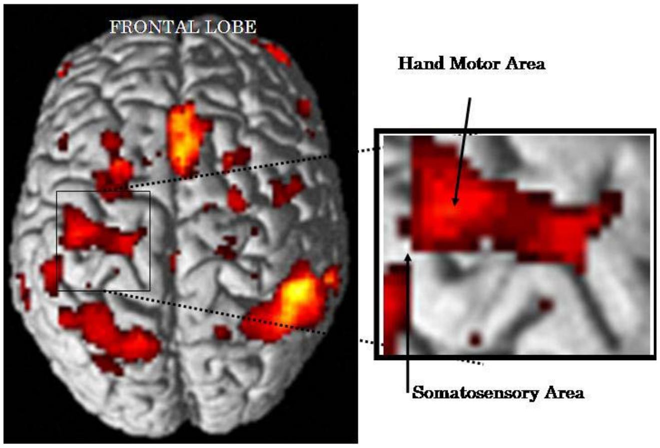

FIG. 4 shows the image resulting after the fMRI scanning for the amputee grabbing a cylinder using the robot hand with electrical stimulation functioning as tactile feedback. The image on the right is the zoom out of the motor and somatosensory area related to the hand and arm. The upper part shows the activation of the motor area in charge of the right hand movement, the lower part shows the reaction from the somatosensory area related to the hand. It is important to notice that the subject does not have the right arm to touch any object.

This makes us think that the brain is correlating the multi-sensorial input as a single event, localizing it in to the right hand (in this case, the prosthetic hand). It is important to notice that the subjects do not interact directly with the object in question, but through the robot hand. They receive only visual feedback through the video display and the stimulation on the left arm.

The application of electrical stimulation does seem to affect the adaptation of the amputee to the use of the prosthetic hand. The application of electrical stimulation as tactile feedback, does allows the body to identify the interaction of the hand with the environment, allowing for a new channel of information to work in benefit of the adaptation to the new “Limb”. Also, the results of our experiments over time show the specialization on the activation area in the brain related to the motor control cortex (MI) and the somatosensory cortex (SI). Another interesting point to discussion is the cross-modality that appears in the brain. In the fMRI scan, the activation of the somatosensory area is related to the right hand, even though the stimulation is performed on the left arm. This make us think of a cross-relation in the brain, between the two lobes, allowing adapting the sensory input and correlating it into a single event. This effect needs to be study with more detail.

These results show the possibility to use the brain plasticity into the generation of new communication channels with the robotic system. The fMRI proved a useful tool to measure objectively the changes in the cortical activation due to the use of the prosthetic system, and allowing a more detailed feedback on the workings of the amputee brain. This allow for a more detailed medical evaluation for the rehabilitation process of an amputee.

The EMG prosthetic hand allows reverting to some extent the process of cortical reorganization that occurs when the brain stops receiving the information from the missing limb. This process is even speed up when the use of the EMG prosthetic hand includes feedback to the body. Our experiments with an amputee shows that the main effect of the electrical stimulation is that the person can adapt easier to the prosthetic hand, and actually develop the “illusion “ that the robot hand is part of her own body, due to the activation on the sensory motor cortex in the brain.

III. CONCLUSION

In the course of these experiments we confirmed the importance of the simultaneous stimuli needed for the brain to correlate events, in order to identify them as a single event, opening new channels in the man-machine interaction. The fMRI is a useful tool to measure in an objective way the changes due to the interaction with the system proposed. Still there are several challenges to deal with, such as electrical noise while inside the fMRI chamber for more practical use. From previous studies in neuroscience, there was the knowledge on the brain workings, that can be use now in order to generate more efficient man-machine interfaces. In this study we confirm the need for more sensorial channels for prosthetic applications. Along with continuous use and training, the correlation between visual and sensorial stimuli can be strengthened, allowing the development of a more close relationship. In the future work, we expect to continue measuring the development in the sensorial cortex due to continuous use of the prosthetic hand with sensorial feedback..

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