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Preliminary results of BRAVO Project

Brain computer interfaces for Robotic enhanced Action in Visuo-motOr tasks

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Abstract — **This paper presents the preliminary results of the project BRAVO (Brain computer interfaces for Robotic enhanced Action in Visuo-motOr tasks).The objective of this project is to define a new approach to the development of assistive and rehabilitative robots for motor impaired users to perform complex visuomotor tasks that require a sequence of reaches, grasps and manipulations of objects. BRAVO aims at developing new robotic interfaces and HW/SW architectures for rehabilitation and regain/restoration of motor function in patients with upper limb sensorimotor impairment through extensive rehabilitation therapy and active assistance in the execution of Activities of Daily Living. The final system developed within this project will include a robotic arm exoskeleton and a hand orthosis that will be integrated together for providing force assistance. The main novelty that BRAVO introduces is the control of the robotic assistive device through the active prediction of intention/action. The system will actually integrate the information about the movement carried out by the user with a prediction of the performed action through an interpretation of current gaze of the user (measured through eye-tracking), brain activation (measured through BCI) and force sensor measurements.**

Keywords – Upper limb; Arm exoskeleton; Gaze Tracking; Hand exoskeleton; Brain Computer Interface

I. INTRODUCTION

Impairment of finger, hand and arm function is a common outcome following stroke or peripheral nerve injury, often resulting in chronic functional deficits. Well-established traditional stroke rehabilitation techniques rely on thorough and constant exercise [1]. Early initiation of active movements by means of repetitive training has proved its efficacy in guaranteeing a good level of motor capability recovery [2] during the acute stroke phase. However, permanent disabilities are likely to be present in the chronic phase, especially concerning upper extremities [3]. Several research studies have recently focused on both the development of novel robotic interfaces and the use of Virtual Reality (VR) technologies for rehabilitation. The former may overcome some of the major limitations that manual assisted movement training suffers from, i.e. lack of repeatability, lack of objective estimation of rehabilitation progress, and the high dependence on specialized personnel availability. On the other hand, VR-based rehabilitation protocols may significantly improve the quality of rehabilitation by offering strong functional motivations to the patient, who can therefore be more attentive to the movement to be performed. A recent survey [4] outlines that robotic-aided therapy allows a higher level of improvement of motor control if compared to conventional therapy. Several studies [4] have demonstrated positive effects of VR on rehabilitation, which enhances cognitive and executive functions of stroke patients [6] by allowing them to receive enhanced feedback on the outcome of the rehabilitation tasks he/she is performing. Moreover, VR can provide an even more stimulating videogame-like rehabilitation environment when integrated with force feedback devices and more specifically exoskeletons interfaces, thus enhancing the quality of the rehabilitation [7].

However, VR presents the limit of not being able to guarantee a coherent alignment of visual and proprioceptive sensory stimulation. Stereoscopy, due to issues of patient's usability, is still not employed in rehabilitation training, and so the perception of depth in the visual representation of the task should rely only on visual cues such as perspective, shadows and occlusions among objects. It has still not been studied how this misalignment of sensory modalities can affect the functional recovery in stroke, since a quick adaptability of patients to such a sensory misalignment is observed as well.

For this reason and for accelerating the transfer in Activities of Daily Living (ADLs), it becomes more and more interesting being able to propose to the patient rehabilitation tasks in a real setting, with the active assistance provided by the robot. But in this scenario how is it possible to actively guide the impaired limb toward the object to be reached and grasped? In this context, the BRAVO project ("Brain computer interfaces for Robotic enhanced Action in Visuo-motOr tasks") will aim at enhancing the classical feedback control schemes through a novel neuro-feedback generated by a model of user's *attention* and *gaze*. Such additional feedbacks will be introduced for predicting the intended action of the patient.

The BRAVO system proposes a new paradigm shift in the control of exoskeletons and active orthoses for rehabilitation and assistance in ADLs. The classical approach to rehabilitation and assistive robotics is based on a robot, whose action is activated by the user's movement detected by means of force and position sensing. This is not a reliable way of controlling the robot when the user is motor impaired and so can present spasticity, tremor, reduced motor function, muscle weakness. Current limitations of existing devices rely in the lack or reduced capability to predict the intended action of the patient. The innovative approach of BRAVO makes use of the information arising from the user's attention and intention, detected by means of eye-tracking, scene analysis and BCI, to enhance the motor assist through the prediction of user's intended movement.

Since sight normally anticipates movement, and saccade movements of the eye are normally performed directing the gaze on the target before beginning the arm/hand's movement [8], this information can be used to enhance, ahead of real start of movement, the user's bio-feedback to obtain an adaptable robot to user's behavior. In this respect, the robotic systems developed within BRAVO will be extremely innovative compared to already existing assistive technologies: they will be based on state of the art robotic technologies, e.g. exoskeletons, where classical feedback control schemes are adopted based on movement and force detection, but enhanced through a novel neuro-feedback generated by a model of user's attention and gaze and guided by user's eye-tracking.

In this paper the general aim and scientific objectives of the BRAVO project are presented, giving an outline of the preliminary results obtained that show the feasibility of the proposed research.

II. THE BRAVO PROJECT

The BRAVO project aims at the implementation of an assistive robotic rehabilitation system for arm and hand. The reference scenarios that are considered are the typical tasks involved in ADLs, focusing in particular on reaching, grasping and pick and place operations. The patient will sit on a chair and will be able to reach, grasp and move objects in front of him with his own hands.

The innovative approach proposed in BRAVO consists in using BCI and Eye Gaze Tracking (input systems) for predicting the user intentions and a robotic arm exoskeleton and hand orthosis (output systems) for assisting the user in performing the tasks. The final objective is to allow the use of robotic systems also to patients that suffer from hard neurological injuries that cannot be treated with traditional controlled robotic devices.

In Figure 1 the architecture of the overall system is presented. The working principle is based on a set of input devices: eye tracking&cameras, position and force sensors and BCI. Such inputs are properly processed in order to recognize the object that the user has planned to grasp, the position of the object and the intention of starting the grasp closure.

Two output devices are used for assisting the user movements. The first one is an arm exoskeleton [9] and the second is novel hand orthosis that is currently in development.

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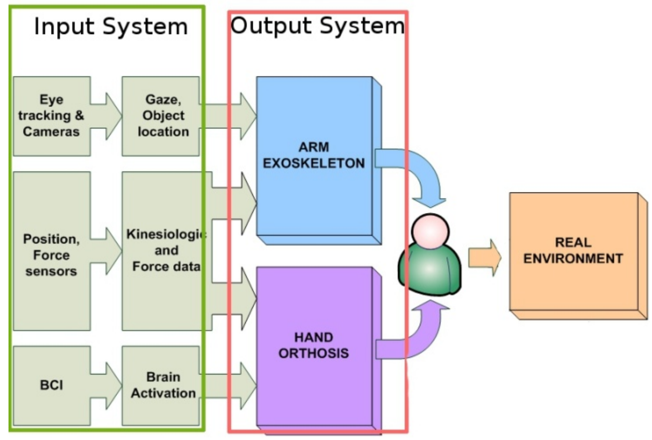

Figure 1. BRAVO system architectur scheme

The system functionalities can be illustrated with reference to Figure 2 through the following sequence of operations:

1. the user sits on a chair in front of a table with several objects that can be grasped with one hand;
2. the user decides to grasp and move an object
3. the user looks toward the object that he/she is going to grasp
4. the eye tracking system will get the direction of gaze;
5. the camera mounted on the user's head will identify the object
6. a second camera will detect the object position;
7. the arm exoskeleton will be controlled in order to assist the user in reaching the object and orienting the hand for preparing the grasping phase;
8. the user decides to close his hand;
9. his intention is detected by the BCI;
10. the hand orthosis will assist the user in the grasping movement.

Object placing and hand opening will be assisted with analogous procedure.

The development plan for the achievement of the complete system has been divided into the following phases:

- Development of Reaching Control arm exoskeleton based on the eye gaze tracking;
- Development of Grasping Control of the hand orthosis based on BCI
- Development of a novel hand orthosis
- Integration of the control and the robotic devices in a single multipurpose system

Currently the two control strategies has been implemented and tested. The Grasping control has been implemented with a temporary setup of a haptic hand exoskeleton. Moreover a preliminary design of the hand orthosis has been conducted.

In the following section we report the description of the developed setups and some preliminary experimental results.

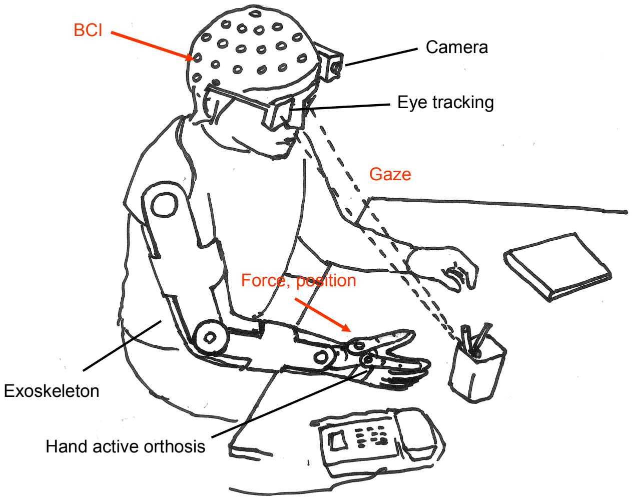

Figure 2. Working principle of the BRAVO system

III. PRELIMINARY RESULTS

A. *Reaching Control results*

In this work the eye-tracking is used for the control of a wearable exoskeleton for upper limbs motor support for reaching tasks.

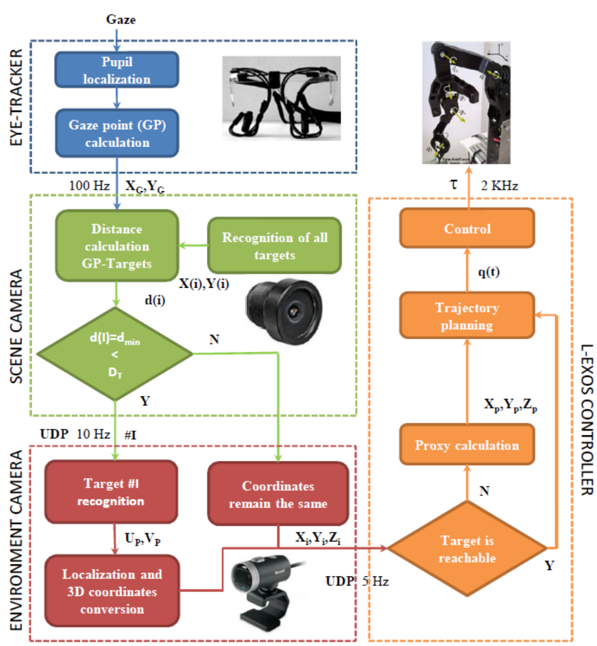

Figure 3. Scheme of the L-Exos controller based on intent prediciton

The main components of the controller, depicted in the scheme of Figure 3, are:

- Eye Tracker to detect to direction of gaze in order to select the object that the user intends to reach;
- Scene Camera to be used in association with the eye-tracking to select which target the user is looking at;
- Environment Camera to locate the target in 3D space and communicate the target position to the controller;
- The L-Exos controlled through a trajectory planner that sets the trajectory of the user arm according to the previously detected object position.

Basically the eye tracker continuously measures the gaze direction. Integrating the information of gaze direction with the images from the scene camera it is possible to identify the object that the user has selected. Through the environment camera the position of the object is detected and communicated to the L-Exos controller. The controller plan a trajectory through a novel algorithm (presented in the next paragraphs) taking into account the workspace limitations of the robotic device. The setup of the realized system is shown in Figure 4 and the two main components are presented in the next paragraphs.

Figure 4. Eye-tracking based system for target selection and reaching

1) *Light Exos Controller*

Light exoskeleton (L-Exos) has been designed at PERCRO laboratory in 2003 [9]. It has five degrees-of-freedom (DoF), four of them fully actuated and the last one for wrist pronation/supination motion is passive but sensorized. L-Exos is attached to the user arm in three points: the shoulder, the forearm, and the wrist (handpalm). The anthropomorphic kinematics of the device allows to identify each DoF of the device with the equivalent human motion: (1) Adduction/ abduction; driven by joint q_1. (2) Flexion/extension; driven by joint q_2 and q_4. (3) Internal/external rotation; driven by joint q_3. (4) Pronation/ supination; given by q_5, see Figure 5.

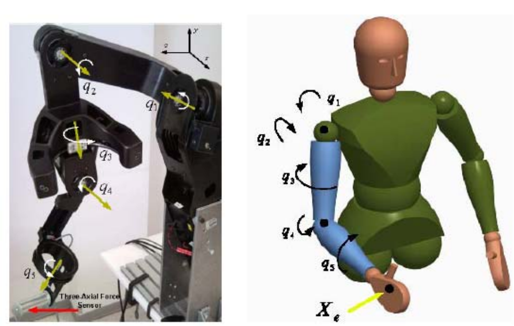

Figure 5. The L-Exos kinematic scheme

An important characteristic of the L-Exos is the concavity of the workspace in Cartesian space (Figure 6). In this type of workspace there is not always a straight line that links two generic points. It follows that the generation of a suitable trajectory that connects any two points of the workspace is required. For the L-Exos two efficient trajectories planning strategies are implemented to overcome the issue:

- in Cartesian space the planned trajectories tend to be minimum-length and predictable under a space occupancy point of view thanks to an online trajectory planning method based on quantization of the space [10].

- in joint space the planned trajectories permit to have less mechanical and kinematic solicitations on the manipulator and subsequently on the arm of the subject (that is linked to the exoskeleton) thanks to a new online synchronized bounded jerk trajectory planning method.

Both methods permit to operate in safe conditions thanks to the proxy point calculation concept.

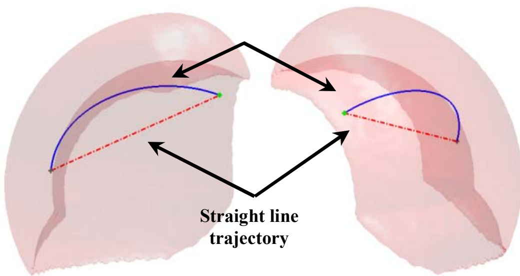

Figure 6. A model of the L-EXOS workspace obtained through quantization method. The workspace is concave

In reaching tasks not all the possible points of the space that the user can select through the eye tracking system can be reached by the robotic device. So the L-Exos controller always check if the target point is reachable and if the object is out of the workspace a proxy point is calculated. The proxy point is defined as the closest point to the target inside the workspace of the manipulator that belongs to the line that links the present position of the end-effector and the target point. So we have the certainty that every times the end effector of the L-Exos does not try to reach point outside of its workspace.

2) Gaze Tracking System

The eye-tracker system used in this project is the Binocular eyeframe mounted scene camera system by Arrington Research®. It is composed by a pair of glasses equipped with two infrared cameras for the eyes, two infrared LEDs and one wide-angle camera for the scene (89°) ("scene camera"). Arrington Research provide also a software tool for calibrating the eye-tracker creating a correspondence between the gaze direction and the scene camera. In this way it is possible to project the gaze direction of each eye onto the scene camera image plane.

A practical case study has been conducted to show the results obtained with the presented system. The subject has to perform a simple task that is to reach and grasp a box and move it to another location only actively moving his hand. The arm remains passive and is moved by the L-Exos. The selection of the target will be performed only looking at a target.

Every step of the experiment is showed in Figure 7. Every subfigure is composed by four panel. The panel on the top-left reports the view of an external camera that records all the working scene, while the right panel reports the scene camera point of view with superimposed signs that indicates the target positions, the projection point of the gaze and the color of the chosen target. The panel on the bottom-left gets the environment camera point of view with superimposed signs that indicate the chosen target and its position in the image. The last panel figures one of the infrared camera on the glasses point of view.

In particular, the studied timeline in the case study is:

- at time t_0 the hand is over the green target in rest position and the subject looks at the blue target over the box and the system readily locates it (Fig. 7.a);
- at time t_1 the subject reaches the box and grasps it. In the meanwhile he looks at the new position of the box marked with the red target (Figure 7.b).

The reaching task has been preliminary tested with some volunteers and successfully demonstrate the functional integration of the subsystems.

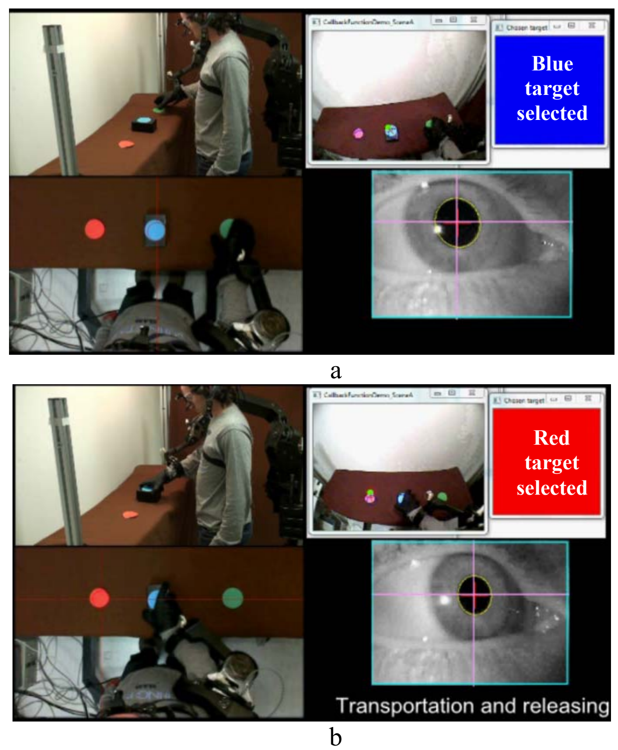

Figure 7. State of the experiment at time t0 (a) and t1 (b)

The advantages of the proposed solution are:

- the efficiency of the use of a cheap commercial eye-gaze glasses;
- the accuracy of the estimation of the gaze direction thanks to cameras that record only the eye area and not the face area;
- the possibility to use the system without head tracking;

- the proposal of an alternative solution of the “Midas touch” problem [11] to the dwell time. The proposed solution is to set a threshold on the distance between the projection point of the gaze onto the scene camera image plane and the center of mass of a recognized target in the same space. Only if the distance between the projection point and a target is less than the threshold, the target is chosen.

B. Grasping Control results

Grasping control is achieved by the prediction of intent of the user through EEG recording system. A commercial device g.GAMMAsys and gUSBamp by Guger Tech is used for implement a customized BCI interface for controlling the position and applied force of the hand orthosis.

A preliminary test of the only BCI system has been conducted coupling the BCI system to a graphic virtual hand controlled by the user. The system uses active electrodes applied onto the user head through an elastic cap and an electrically conductive gel. The analog EEG signals are conditioned and sampled by a signal processing device and then sent to the BCI classifier algorithm executed onto a control PC. In the experimental setup, the subject sits relaxed on an armchair in front of a screen. The subject wears the EEG recording cap with electrodes placed in bipolar configuration at the level of the motor cortex.

During the first training phase the subject is told, through a graphical cue visualized on the screen, to perform an imaginary action of grasping or relaxing the right hand. The recorded data is then used to train a linear discriminant classifier operating on the power values of the frequency bandwidths of the alpha and beta brainwaves. Then, a second training session is performed showing the subject a feedback output of the classifier, in order to improve his motor imagery.

Figure 8 shows the measured spectral power maps on the scalp related respectively to the alpha and beta frequency bands and to the relaxed and motor imagery state. As it can be noted, the difference between the relaxed and motor imagery state enables the classifier to differentiate the subject’s intention of grasping from the intention of relaxing his hand.

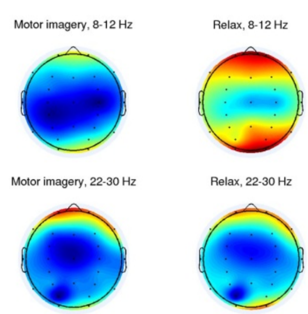

Figure 8. Spectral power maps related to the alpha and beta frequency bands for motor imagery and relaxed state.

After the preliminary experiments involving the only BCI system, a complete BCI-controlled robotic system has been developed and implemented.

With the aim of anticipating the design and testing of the control of the hand orthosis through BCI interaction, we built a preliminary setup that makes use of a haptic hand exoskeleton [12] that is already available at our laboratory facilities. Such device is used for preliminary test only since it was originally developed for haptic interaction and do not perfectly match the functionalities and specifications of a hand orthosis. Figure 9 shows some details of the hand exoskeleton. Basically, it is a two finger (index-thumb) device able to generate 3 DoF forces in the range of ±5N with high resolution. It is characterized by an anthropomorphic kinematics using special mechanisms that implements remote center of rotation.

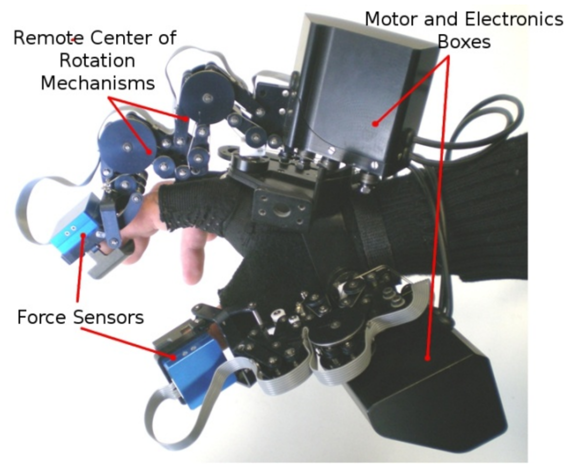

Figure 9. Hand exoskeleton used for preliminary test of BCI control

The BCI-controlled hand exoskeleton system is composed of the following elements, as shown in Figure 10: the EEG recording system and the Hand Exoskeleton discussed before, and a control PC, used for executing both the BCI classifier algorithm and the Hand Exoskeleton control algorithm.

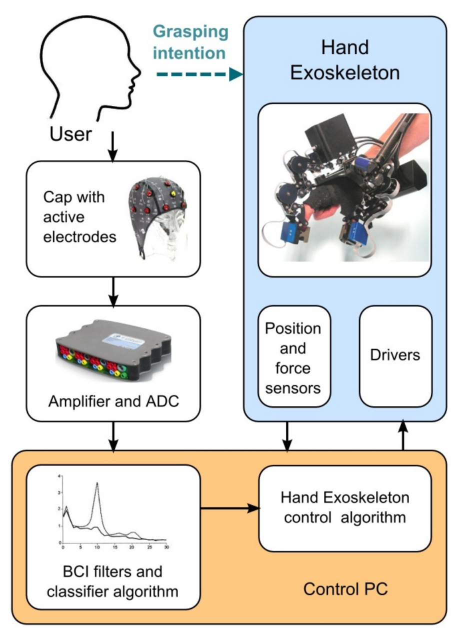

Figure 10. BCI controlled Hand Exoskeleton general hardware layout

The EEG signals recording and analysis process is the same of the BCI system discussed before. The information extracted from the classifier processed data is now used to modulate a position and force reference signal. The reference signal is sent to the Hand Exoskeleton control algorithm, in order to perform the subject's identified task.

The preliminary setup of the BCI-controlled Hand Exoskeleton system aims at testing the capability of the system to identify a basic grasping intention imagined by the subject, and to perform a similar task through the Hand Exoskeleton.The experimental setup is similar to the previously discussed BCI experiment. In the actual setup however the subject's hand is linked to the Hand Exoskeleton (Figure 11). After the training phase, the user performs imaginary tasks of grasping and relaxing the right hand. The BCI classifier algorithm analyzes in real time the measured EEG signals, and the feedback provided by the classifier is then used to modulate a position and force reference command sent to the Hand Exoskeleton. The improvement of the actual system is that, after the first training session, the user can optimize the training efficiency through the feedback given by the real execution of the task performed by the Hand Exoskeleton.

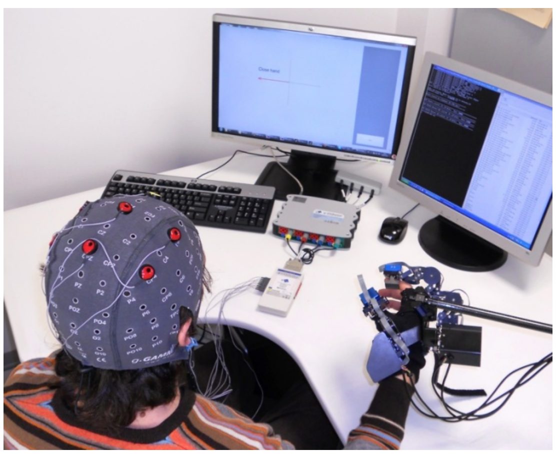

Figure 11. Preliminary set-up of the BCI controlled Hand Exoskeleton

C. *Preliminary design of a novel hand orthosis*

Aiming at the development of a new hand exoskeleton, the scientific literature has been firstly analyzed to define the users' requirements and the device technical specifications. As for the grasping phase the finger extension, the control of the grip force while closing the hand around an object with a certain shape and the motion coordination of the fingers for fairly complex functions can be very difficult tasks for post-stroke patients, due to several possible sensory-motor deficits [13]. .A number of hand exoskeletons with peculiar features have been developed in the last decade. Depending on the specific tasks that the devices were developed for (e.g. rehabilitating the power grasp or the pinching, or the ability of finger fractionation), they present different kinematic schemes, actuation systems (generally electric or pneumatic), control strategies, and overall complexity. In particular exoskeletons with limited or multiple DoFs have been proposed, ranging from hands with 2 DoFs in all [14–16] to five-fingered hands with 4 DoFs per finger [17] A review of the rehabilitation hand exoskeletons has been proposed by the authors in [18].The focus of the rehabilitation protocols of BRAVO is on the training of patients in the acute phase, with the aim of recovering the basic functions of manipulation. In this context, two main functions should be possibly assisted by the hand exoskeleton, namely the finger extension for correctly pre-shaping the patient's hand when approaching the target and the control of motion and force of the fingers when grasping the object. A hand exoskeleton having 2 DoFs oriented to assist the power grasp was defined as the target solution for the first prototype to be realized. One motor is devised to actuate the thumb flexion/extension whereas a second motor actuates the flexion/extension of the combination of the other four fingers. The independent action of the thumb with respect to the four fingers is needed to properly control the motion coordination in order to correctly grasp the object. The exoskeleton mechanism must couple the flexion/extension movements of the three joints of a single finger, whereas the abduction/adduction of the metacarpophalangeal joint is inhibited.

The design of a planar mechanism with 1 DoF, whose topology has been conceived as suitable for all the fingers, is in progress. Figure 12 shows the schematic of the finger exoskeleton, that from the kinematic point of view is a six-bar mechanism: link 1 is the frame, links 2, 4 and 6 correspond to the three phalanges, which are coupled by the bars 3 and 5. In order to steadily and safely guide the patient's hand in the planned grasping trajectory, each finger mechanism will be connected to the corresponding human counterpart at the level of all the three phalanges.

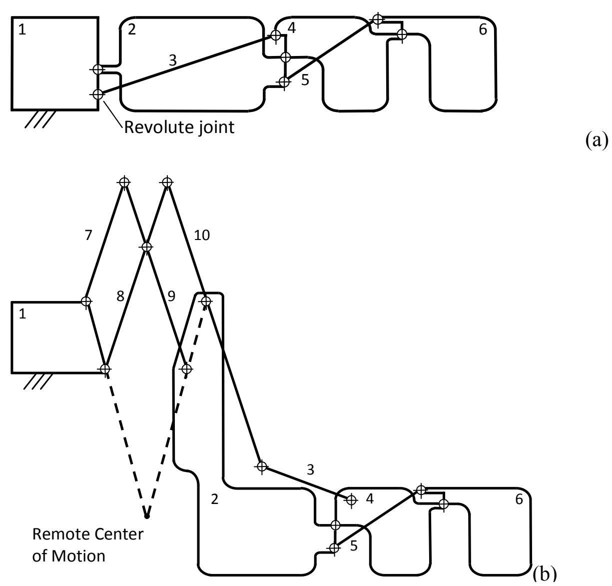

Figure 12. Scheme of th kinematics of the novel hand orthosis

This requires a proper design to avoid interference of the exoskeleton both with the human finger and the grasped object. A number of solutions to correctly avoid an over-constraining of the resulting system (exoskeleton and human finger) are being currently analyzed. By designing a low-stiffness large-displacement compliant mechanism, made of proper plastic materials, the resulting structure can be very thin and compact and thus it can be placed aside each human finger. To this aim, a remote-center-of-motion mechanism must be integrated (at least for the middle and ring fingers) in order to make the exoskeleton first phalange rotate around the metacarpophalangeal joints of the human finger. Figure 12(b) reports a possible solution based upon the combination of two parallelograms (links 7, 8, 9 10). The driving links of the four finger exoskeletons (link 2 and 7 in Fig. 12 (a) and (b) respectively) will be mechanically coupled and connected to the same actuator. A differential mechanism would allow a self-adaptive grasp, but it will be not included in the first prototype for the sake of the system simplicity. A compliant behavior of a single finger to obtain a self-adaptation of the phalanges around the grasped object can be also obtained by properly integrating simple elastic elements, as adopted for the LARM robotic hand [18]. Following the command inputs sent by the BCI, the hand will be controlled using a force-position control scheme, in order both to guarantee the desired function and to respect the rehabilitation robotics paradigm of "assistance-as-needed" [19]. To this aim, position sensors on the driving links of the finger mechanisms and force sensors between the human phalanges and the exoskeletons will be used. The contact area among the human fingers and the grasped object will be kept free so that the grasping force cannot be directly measured. The first prototype will be equipped with many sensors: proper experimental tests will be performed to make a selection of a minimum set of sensors to be used in the final version of the device.

IV. CONCLUSION

This paper presented the preliminary results of the BRAVO project. The project aim at the development of a novel rehabilitation system that integrates the use of robotic technologies and feedback systems to predict the user intentions. A robotic arm exoskeleton called L-Exos has been integrated with a Eye-Tracking system that is able to predict the user intention for reaching movements. An hand orthosis is currently being developed and will be integrated with a BCI for the control of closing and opening movements of the hand for grasping objects. The preliminary results that have been presented show a promising perspective for the future integration of the system. In the next future tests on a first set of patients will be performed.

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