Preliminary Study of a Robotic Rehabilitation System Driven by EMG for Hand Mirroring

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***Abstract*—Robotic devices can be a viable solution in different rehabilitation activities for increasing patients' gains, providing high-frequent, repetitive and interactive rehabilitation treatments. In this paper, the design, development and preliminary characterization of a robotic system for assisted hand rehabilitation, driven by surface EMG measurements, based on the mirroring of healthy hand movements is presented. The healthy hand opening and closing is detected by the muscular activity and this is used to guide a robotic glove moving the paretic hand. The innovative aspects of the research deal firstly in the contemporaneous use of EMG signals and mirroring technique and secondly in the development of an algorithm for the automatic setting of the actuators thresholds. A preliminary system characterization was conducted. The performed tests demonstrate that the system is a viable solution to allow a healthy person to perform exercises of "hand closing" "hand opening", with ON-OFF and proportional controls, with a success rate in tests carried out by 98%. The proposed system is a starting point for a novel approach to hand mirroring rehabilitation on patients with upper-limb motor deficits.**

***Index Terms*— Therapeutic interaction; Robotics; Electromyography; Hand rehabilitation; Signal processing;**

I. Introduction

The main causes of hand disability are traumas, the natural aging of the musculoskeletal apparatus and nervous system pathologies. Among the last category, cerebro-vascular accidents (stroke) are the most frequent. In many western countries stroke is the third cause of death and the leading cause of chronic disability. Approximately, 800.000 people suffer stroke each year in the USA [1], 194.000 in Italy [2], 6000 in New Zealand [3], etc. About two thirds of strokes are non-fatal and eighty percent of survivors are affected by important motor deficit [4], namely hemiparesis with impaired motor control on the affected side. The motor recovery is limited, the percentage of recovery found in the literature varies from 5% to 52% [4]. In the spontaneous recovery of sensorimotor functions, a typical sequence of events occurs: lower limb recovers in advance, upper limb follows and the hand is the last [4]. Therefore, the motor recovery of upper limb and hand is the most critical point. A complete recovery unfolds rapidly, when it occurs; partial recovery, which is more frequent, unfolds over a period that ranges from two to eleven weeks [5]. Between 55% and 75% of survivors continue to experience upper extremity functional limitations, which are associated with diminished health-related quality of life [6]. Patients are helped in restoring lost motor functions with personalized rehabilitation programs [7]. Due to the plasticity of human brain, which is capable of cortical reorganization after damage, rehabilitation training can restore limb functions. For most patients, efficiency, timeliness and continuity of the rehabilitation program are of fundamental importance for the recovery process. Recent approaches for rehabilitation involve repetitive training of the paretic upper extremity on task-oriented activities and give evidence of efficacy among stroke survivors who retain some ability to actively extend the fingers and wrist of their paretic upper extremity [4]. Among these approaches the most used are: constrained induced movement therapy (CIMT) [8], mental practice (MP) [9], bilateral arm training (BAT) [10] and mirror therapy (MT) [11]. Through MT, patients watch into a mirror the movement of the non-paretic arm into a mirror and image the paretic side is doing the same thing. Usually the rehabilitation protocols involve daily training for several weeks, conducted by therapists in a hospital in a one-on-one manual mode. The provision of highly intensive treatment for all patients is often difficult. In recent years, many researchers developed robotic devices for the upper limb rehabilitation, as a useful aid to traditional therapy. Robotic devices can increase patients' gains, providing high-frequent, repetitive and interactive rehabilitation treatments. They can also be used to collect data for monitoring patients' progress. Systems for robot-aided neuro-rehabilitation may be divided into two categories: end-effector robots and exoskeletons. Examples of end-effector rehabilitation robots are: Massachusetts Institute of Technology (MIT) Manus [5], a robotic system designed for upper limb stroke rehabilitation; Mirror Image Motion Enabler (MIME) [12], a device that allows the patient to use the unaffected side to control the impaired one, practicing mirro-image movement; Assisted Rehabilitation and Measurement (ARM) Guide [13], which assists reaching in a straight line trajectory; Bi Manu-Track [14], that enables the bilateral passive and active treatment of forearm and wrist movement; GENTLE/S system [15], that provides robot mediated motor task in 3D space; the 1 DOF wrist manipulator and the 2 DOF elbow-shoulder manipulator developed by Colombo et al. [16], for the upper limb movement rehabilitation. Examples of exoskeletons for the upper limb are: ARMin III [17] with an ergonomic shoulder actuation, commercial mPower arm brace, exoskeleton which uses electromyogram (EMG) signals from the biceps and triceps muscles to generate assistive torques for elbow flexion/extension; the commercial Hand Mentor, a 1 DOF wearable device for the rehabilitation of the wrist and fingers based on air muscles. Rehabilitation robots may operate in different modalities, the most used are: passive movement, active movement or bimanual exercise [18]. Recently, researchers investigated the use of electromyography (EMG) signals in active controls, so that the device reacts to input based on muscles activity. For more than fifty years, EMG signals have been intensively used in the control of prosthetics. Recently, EMG is used in triggered ON-OFF control of rehabilitation robots [19], measuring the muscle activity and applying an assistive torque when a fixed threshold is reached. EMG signals can be used either as control signals or as information for the monitoring of the therapy progress.

In many centers hand rehabilitation systems with EMG as a control input are being developed towards several goals; references [20-24] describe EMG controlled orthotic exoskeletons for the hand, with different constructive and control approaches. In this paper, we present the design, development and preliminary characterization of a robotic system for assisted hand rehabilitation, driven by surface EMG measurements, based on the mirroring of healthy hand movements. The healthy hand activity is detected by the muscular activity and this is used to guide a robotic glove, which moves the paretic hand. Such a methodology can be included in the field of the mirroring techniques. The subject performs rehabilitation exercises in front of a screen that shows the correspondent healthy hand movement obtained in real time by a camera. This approach allows the neuronal mental reconstruction of the movement, because the subject seeing the video has the feeling of moving unaided the impaired hand. The innovative aspects of the research deal firstly in the contemporaneous use of EMG signals and mirroring technique and secondly in the development of an algorithm for the automatic setting of the actuators thresholds.

II. System Description

A. *Structure of the robotic rehabilitation system*

Fig. 1 shows the diagram of the rehabilitation robotic system based on EMG measurements proposed for hand mirroring exercises. It consists of four main modules: signal conditioning and acquisition, feature extraction, rehabilitation system control and rehabilitation glove. The first module of signal conditioning and acquisition measures EMG signals and also filters out noises. Subsequently, the filtered EMG signals are sent to the feature extraction module to identify certain parameters used in the control algorithm, which is implemented in the actuator control module. It consists of a Personal Computer (PC) with a proposed software developed with LabVIEW. With the extracted features, another software, implemented in the actuator control module, determines the hand movements and generates the corresponding commands to control the robotic glove. As specified, the designed system is proposed for hand mirroring exercises. During these exercises different hand movements can be performed. However, in this preliminary phase, we have preferred to focus on just one movement that is essential for proper rehabilitation of the hand. Accordingly, the designed system has been implemented to recognize muscle relaxation, wrist and finger extension (which will be termed as “hand opening”), wrist and finger flexion (which will be termed as “hand closing”). We used two electrodes (E1, E2; 5x5 cm each) placed over the extensor digitorum and the extensor carpi radialis to measure the muscle activation during hand opening. Whereas, to detect muscle activation during hand closing, we placed two electrodes (E3, E4; 5x5 cm each) over the palmaris longus and the flexor carpi ulnaris (see Fig. 2). These muscles are called in the following hand opening/closing muscles. One electrode (Er) was used as reference. Each couple of electrodes were connected to a conditioning circuit specifically designed, which will be described in the following paragraph.

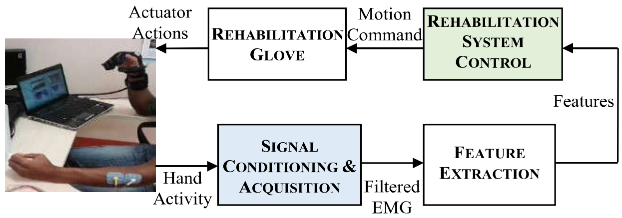

Fig. 1. Block-diagram of the proposed robotic rehabilitation system driven by EMG measurement.

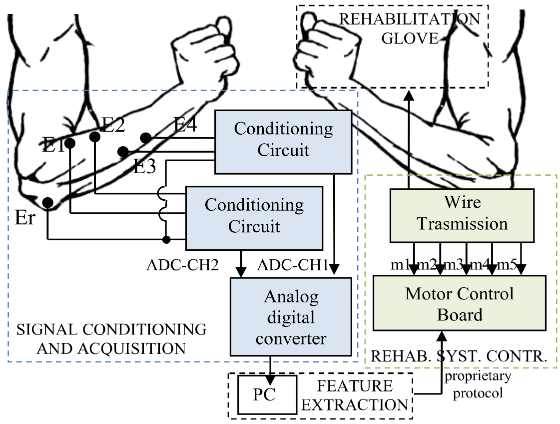

Fig. 2. Block diagram of the measurement system.

Bipolar electrodes are used to reduce the common mode noise using an instrumentation amplifier as a first stage of the conditioning circuit. The purpose of using bipolar electrodes is to eliminate common noise of the two signals from both electrodes. The electrodes are connected to the conditioning circuit board with shield wires. These metal shield wires reduce electromagnetic interference by acting as a Faraday cage. The two output signals from the conditioning circuit (ADC-CH1 and ADC-CH2) are digitized through a NI 9215 cDAQ acquisition board by National Instrument using a sampling frequency of 25 kHz and a resolution of 0.3 mV. Then, the digitized signals are processed by the PC using the software developed with LabVIEW. The aim was to identify different features characterizing the hand activities. With the extracted features, the software implemented in the rehabilitation system control generates the corresponding commands to control the robotic glove for rehabilitation. A proprietary protocol over RS232 is used for the communication between PC and Motor Control Board (Fig. 3). Finally, the adopted rehabilitation glove (GLOREHA) performs neuromotor rehabilitation tasks thanks to visual and audio feedback associated with fingers motion. The labels from m1 to m5 represents the signals for each finger actuators.

B. *Hand rehabilitation glove and actuation system*

GLOREHA (Fig. 3) is a robotic device for passive rehabilitation of the hand

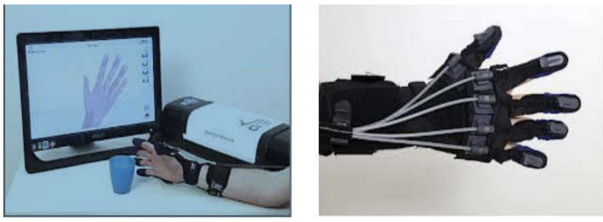

Fig. 3: GLOREHA, the robotic device used.

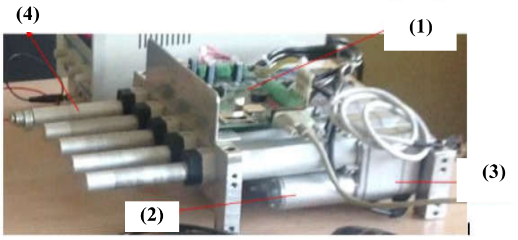

Fig. 4. Motor test bench used in the experimental activity.

The rotary motion of the brushless motor is conveyed to the fingers by push-pull cables that work both in tension and in compression. The fingers can be moved either individually or simultaneously. GLOREHA is adopted to treat patients with paresis or plegia of the hand as a result of injury to the central nervous system. Furthermore, it is used in the post-operative treatment. The innovative aspects of GLOREHA are: the optimal wearability, the possibility to be used either in hospital or at home, the rehabilitation of each finger separately in addition to the hand rehabilitation, the ergonomics suitable for a wide range of pathologies and lightness and transportability. In the preliminary experimental activity, a test bench with actuators equivalent to GLOREHA's motors has been used (Fig. 4). The test bench is formed by a control board (1), five brushless rotary motors (2), five encoders (3) and the shafts (4) linked in the motors. Each motor is dedicated to a finger.

C. *Conditioning Circuit*

The block diagram of the specifically designed conditioning circuit is reported in Fig. 5. The aim was to design a specific circuit for conditioning the signals coming from the forearm so as to maximize the useful EMG signals with respect to noise components with particular attention in low-cost, compact size and portability. Differential amplification technique with bipolar electrode configuration was used to amplify the EMG signals [24]. An instrumentation amplifier (IA) constitutes the input stage, performs the difference between the two floating signals and provides the output as a single ended signal referred to the reference ground. The second and third stages provide filtering. The fourth stage provides a signal amplification. The first stage consists of a high precision instrumentation amplifier (INA128) and the gain amplifier is 10. The selected instrumentation amplifier has high input impedance, thus minimizing loading of the signal source; we used a Burr-Brown INA128 instrumentation amplifier, which has high common mode rejection ratio (i.e. 120dB). High common mode rejection ratio means high capability of the instrumentation amplifier to subtract noise, which appears as common mode signals to the instrumentation amplifier inputs. In the second and third stage, the high pass and low pass filters are cascaded to make a band pass filter. Usually, an EMG signal has a bandwidth between 10 and 500 Hz [24]; thus, the high pass filter eliminates unwanted DC offsets that might be present in the EMG without significantly distorting the EMG signal itself. Furthermore, the EMG signal has large signal contributions around 50 Hz, then we avoided the implementation of a notch filter, but we chose to reduce the power line interference adopting other design strategies (shields, coaxial cables, etc.). The used operational amplifier is LMP7704, which is an output precision amplifier with a CMOS input stage that permits low input bias currents. A 2nd order Sallen-Key filter topology with Butterworth characteristics was chosen due to its capability to provide flat response in the pass band. In order to safely achieve the advantage associated with grounding of the subject, the virtual ground (VG) circuit was used [25]. The principle of VG is to create a low-resistance path to ground for currents of a few microamperes but a large-resistance path for leakage currents higher than 100 µA. Furthermore, the conditioning circuits are powered by two rechargeable 9 V batteries and regulated to ±5 V. Systems, such as this one, utilizing high gain and high performance operational amplifiers require special care in power supply isolation and filtering.

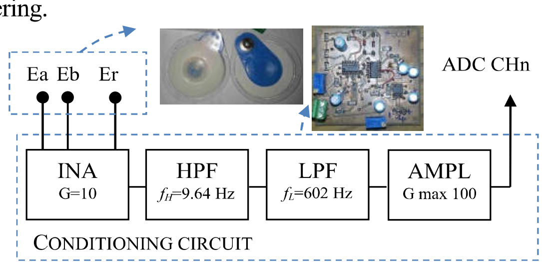

Fig. 5. Block diagram of the conditioning circuit for one channel.

III. Signal Processing

Signal from the aforementioned conditioning device is then acquired at a 25 kHz-sampling rate, using a compact acquisition board with 16bit resolution over 10V full scale. As a tradeoff between processing time and readiness of the system, all data are processed in blocks of 20000 samples each, granting a spectral resolution of 1.25Hz. The signal of each channel is divided in 1 s width windows with a 99.5% overlapping between windows, ensuring a temporal discretization of 5ms. As suggested by various literature [26], root mean square (RMS) could be better suited as a control signal than the envelope of a rectified sEMG signal, therefore for each of these windows the RMS value is computed as shown in eq. 1, where sEMG is the filtered signal and $sEMG_{RMS}$ is its RMS value. The effect of these filters are clearly visible in Fig. 6, which shows sEMG compared to $sEMG_{RMS}$ during four repeated hand openings and closing movements. The position control signal Y, proportional to the $sEMG_{RMS}$ value, is computed from the difference $DIFF_{RMS}$ between hand opening (EXT_{RMS}) and hand closing (FLX_{RMS}) signals, the latter multiplied by a gain factor G to make it comparable to the former, using four thresholds T, as displayed in eq. 2 and eq.3.

$$sEMG_{RMS}(t) = \sum_{t-0,5}^{t+0,5} sEMG^2 \tag{1}$$

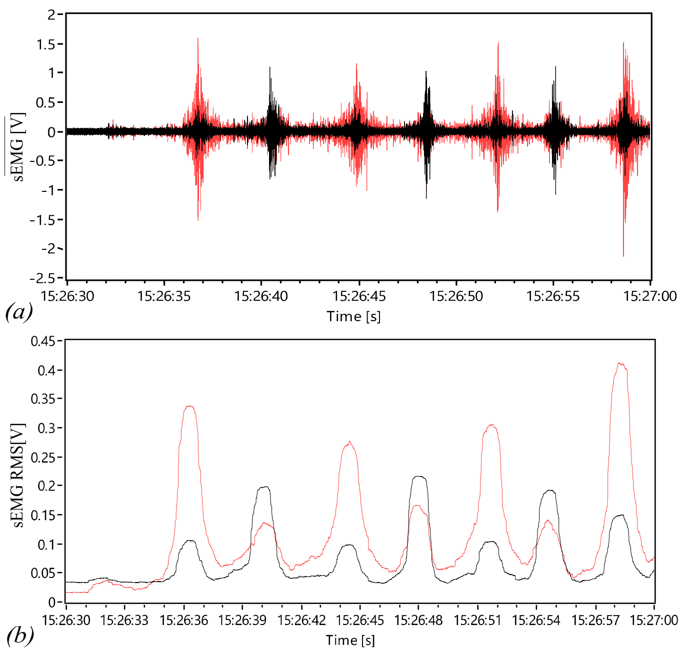

Fig. 6. sEMG signal (a) and $sEMG_{RMS}$ signal (b) of hand closing muscles (in red) and hand opening muscles (in black).

$$DIFF_{RMS} = EXT_{RMS} - G \times FLX_{RMS} \tag{2}$$

$$Y = \begin{cases} Y_{\max}, \ if \ DIFF_{RMS} > T_4 \\ \frac{y_{\max} - y_{\min}}{T_4 - T_3}(DIFF_{RMS} - T_3), \ if \ T_3 < DIFF_{RMS} < T_4 \\ 0, \ if \ T_2 < DIFF_{RMS} < T_3 \\ \frac{y_{\max} - y_{\min}}{T_1 - T_2}(DIFF_{RMS} - T_2), \ if \ T_1 < DIFF_{RMS} < T_1 \\ Y_{\min}, \ if \ DIFF_{RMS} < T_1 \end{cases} \tag{3}$$

This is made to create a dead zone, avoiding small movements due to signal noise while at rest, and creating a linear relationship between sEMG activity and target position, which is constrained between its higher (Ymax) and lower (Ymin) limits. The thresholds required by equation 3 could be set up assessing both the subject's maximum voluntary contraction (MVC) and the relaxed state sEMG value. However, the difficulty of obtaining such values, in most clinical environments and with impaired subjects [27] leads to the development of an auto-tuning algorithm for the evaluation of T1, T2, T3, T4 starting from recorded sEMG signal, as described in paragraph 5. As reported in [28] this approach, combined with the auto-tuning algorithm defined in paragraph V, is able to minimize problems associated with a measurement uncertainties due to low signal to noise ratio (in our case 12 dB) or resolution (in our case 0.3 mV). For this reason, the algorithm performance evaluation was focused on its sensibility ratio and on the timing issues, as reported in paragraph VI.

IV. Motion Control

In this preliminary study, two kinds of control for GLOREHA have been considered: triggered ON-OFF control and proportional control. Different studies have been conducted for both kind of control in EMG applications like [29] for proportional control and like [22] for ON-OFF control. Fig. 7 shows the behavior, in a sequence of hand opening and closing, of the signal passed to the control module, named "command signal" in the following. In the ON-OFF control, two thresholds are needed to detect "Hand Opening", "Hand Rest" and "Hand Closing". For each state, a command is sent to the actuators in order to open, stop or close the hand at a predefined speed. For a generic proportional control, thresholds are also crucial to define a dead band in which EMG_{RMS} values do not produce any unwanted motor motion (four thresholds are needed in this case). Outside this dead band, a command proportional to the signal is sent to the actuators. Through RS232, each finger position set point can be imposed to the motion control loop by the EMG_{RMS} signal processor. The motors are then moved at a preselected speed while the desired position is not reached. The set point can be updated only when the previous final position is reached: this limitation prevents the continuous motor control needed for proportional EMG_{RMS} control. For this reason, only a discrete motion control can be implemented linking a specific position set point to a muscle contraction EMG_{RMS} threshold.

GLOREHA DC motor speed is limited to 16-24 mm/s (depending on the load) and the maximum excursion is 100 mm. This means a minimum motion time for a complete motor excursion of about 6 s. This limitation has been considered sufficient to make proportional position control loop and speed control loop oversized with respect to the preliminary tests.

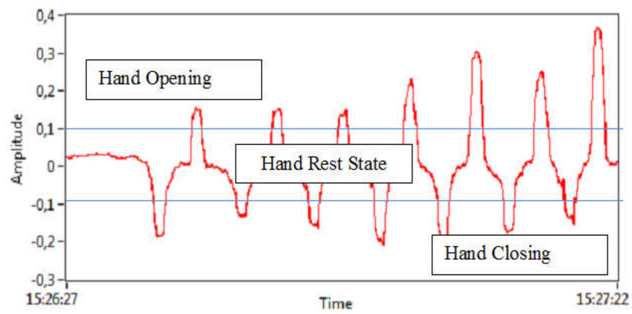

Fig. 7. Example of thresholds on EMG_{RMS} signal.

V. Autho-tuning Algorithm

The gain factors, as well as the thresholds, are assessed using an automated procedure, which does not require MVC recording or relaxed state. The subject under scrutiny is asked to repeat the desired movement and then pause for 1 second, for 9 times during a preliminary procedure, after that the overall RMS value of the hand opening sEMG signal, including pauses, is divided by the overall RMS value of the hand closing sEMG signal, to compute G value, as shown in equation 4. As pointed out by [30], the reliability of $sEMG_{RMS}$ is strongly influenced by the amplitude probability distribution (APD) of the raw signal; therefore, the thresholds are computed starting from the APD statistical analysis. After computing G, as stated before, an ancillary $DIFF_{RAW}$ signal has been computed as the difference between the raw sEMG of hand opening muscles and the raw sEMG of hand closing muscles multiplied by G, as in the following equation 5. The amplitude probability distribution of the $DIFF_{RMS}$ signal is then computed, an example of which could be seen in Fig. 8, to assess which values are more commonly found during the desired movement. To automatically identify a lower and upper limit, to saturate the drive signal, the 1st, and 99th percentile of $DIFF_{RMS}$, computed from the APD cumulate, are used as values for T1 and T4. Analogously, for T2 and T3 value are set equal to the 35th and 80th percentile of the APD of $DIFF_{RMS}$., which identify the rest phase, being the limits of the most occurring values interval.

$$G = \frac{\sum_t sEMG^2_{EXT}(t)}{\sum_t sEMG^2_{FLX}(t)} \tag{4}$$

$$DIFF_{RMS}(t)=sEMG_{EXT/RMS}(t)-G*sEMG_{FLX/RMS}(t) \tag{5}$$

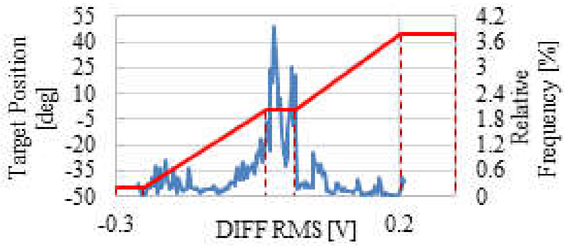

Fig. 8. $DIFF_{RMS}$ APD for a setup run of 9-repeated setup movement of the hand opening and closing (in blue, right-side scale) and computed target position (in red) using percentile values as thresholds.

VI. Preliminary Experimental Tests

Preliminary tests were performed on a right-hander healthy subject (which henceforth will call the subject), male, 22 years old. The tests were carried out at the University of Brescia in the presence of orthopedic medical specialists in rehabilitation (Fig. 9).

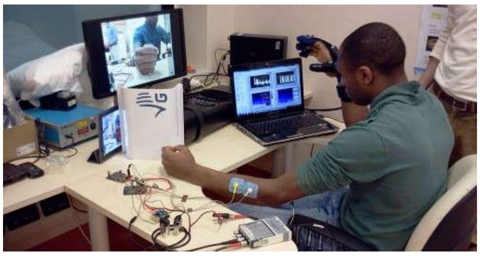

Fig. 9. Experimental setup of the tests and of the preliminary characterization of the system of rehabilitation of the hand applied on a healthy subject (phase 4).

The subject was asked to sit on a chair with the left elbow resting on a table. The electrodes were positioned on the left forearm of the subject (as explained in section 2) while the glove of GLOREHA is worn on the right hand. The electromyographic signal measured on the healthy arm is used to control a virtual hand. The software for the generation of the virtual hand, called "Virtual Hand", was developed with Delphi by Polibrixia s.r.l. The subject is positioned in front of a screen where the image of the healthy hand detected in real-time from a video camera is projected, in order to facilitate mental reconstruction of the movement. Initially, the subject was required to relax the limb, in order to detect electromyographic signals in the absence of muscle activation, and then electromyographic signals relating to a sequence of nine movements of hand opening and closing were acquired for auto-tuning algorithm. Completed this task, the robotic system was activated and a sequence of twenty movements of hand opening and closing were executed. Tests were conducted with ON-OFF control and with proportional control.

Fig. 10 shows the trends of the electromyographic signal, the RMS value of the electromyographic signal and the movement of the actuator relative to a test with ON-OFF control, whereas in Fig. 11 the evolution of the same quantities is related to a test with proportional control.

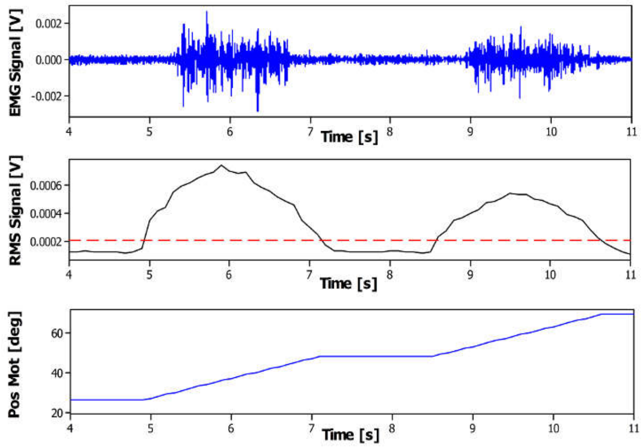

Fig. 10. Results of the experiment carried out to test the control ON \ OFF. Graph A represents the hand-closing muscle contraction, its RMS value B and C the motor movement that was generated.

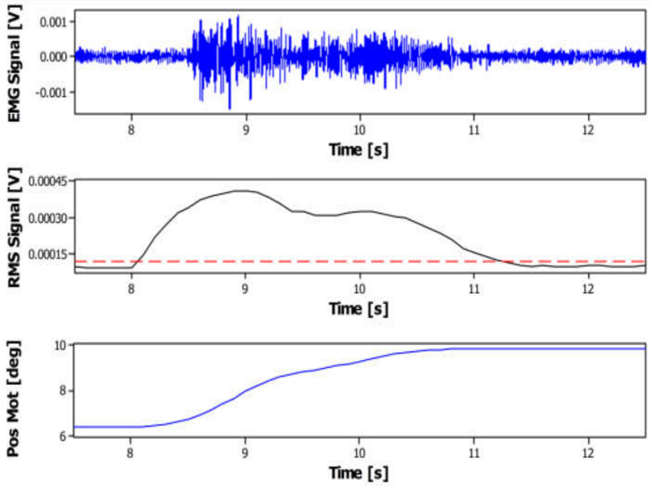

Fig. 11. Results of the experiment carried out to test the proportional control. Graph A represents the hand-closing muscle contraction, its RMS value B and C the motor movement that was generated.

The described test was repeated 5 times, for a total of 100 opening and closing movements, with results reported in Table I. Detection rates were determined by interviewing the subject and the method sensitivity was computed as the ratio between movements detected correctly and the total of movements.

From these tests, it was observed that the movement of GLOREHA is not perfectly synchronous with the motion of the healthy limb, and delays both occur in the onset and offset of the movements. The delays are, as a general average 2.2 s, accounting for about 40% of the movements, but with a high variability (SD=15%), which has to be linked to uncontrolled parameters such as the movement motion law, which was freely chosen by the subject, the sweating and the force exerted on the tendons. The main contribution to these delays is given by the observation time window used to compute the RMS value, which directly translates in a response delay and accounts 1 s of the average 2.2 s overall delay. The remaining part of the recorded delay is likely due to the communication and the computational processing cost.

The tests were repeated with 10 different subjects to verify the robustness of the system against the physical characteristics of the people. The subjects were divided into three categories: burly, medium-size and thin. Table II resumes the obtained preliminary results. The identification of the subjects' physical characteristics was evaluated currently only through subjective observations. It can be observed that at the increasing of the adipose tissue in the subject the sensitivity of the systems decreases (but it is still high) and that the opening sensitivity is always better than the closing one.

TABLE I. MOVEMENT DETECTION RATES FOR A TOTAL OF 100 MOVEMENTS.

	Correctly Detected	False positive	Not detected	Sensitivity
Opening	98	0	2	98%
Closing	93	1	7	93%

TABLE II MOVEMENT DETECTION RATES FOR DIFFERENT PHYSICAL CHARACTERISTICS.

	Burly	Medium-size	Thin	Total
Opening Sensitivity	84%	86%	91%	87%
Closing Sensitivity	78%	82%	88%	83%

VII. CONCLUSIONS

The preliminary study of this rehabilitation robotic system can be a starting point in the implementation of an innovative method of rehabilitation, which combines the use of electromyographic signals and the mirroring technique. The development of the control logic has highlighted the importance of setting the thresholds. To automate this critical stage of the procedure, an algorithm for automatic identification of threshold values giving excellent results has been developed. A preliminary system characterization was conducted identifying an experimental estimation of some significant parameters, such as the percentage of correct operation and the delay in the movement. Future research plans to combine this system with a system for monitoring the finger movements by means of bent sensors to develop a robotic system that can integrate the monitoring of finger movements and the force control with a control feedback in a single device.

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