An EMG-controlled Exoskeleton for Hand Rehabilitation

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Abstract— **The principal goal of this work is the development, testing and experimentation of a device for the hand rehabilitation. The system we designed is intended for people who have partially lost the ability to control correctly the hand musculature, for example after a stroke or a spinal cord injure. Based on EMG signals the system can "understand" the subject volition to move the hand and thanks to its actuators can help the fingers movement in order to perform the task. In this paper we describe the device and discuss the first results conducted on a healthy volunteer.**

I. INTRODUCTION

The main goal of this work is the design and experimentation of an actuated exoskeleton for the functional hand recovery of a subject affected by stroke or other motor diseases. The machine allows the rehabilitation reducing the physiotherapist intervention at the minimum indispensable. Using EMG signals, directly measured from the subject limb, the system predicts the intention to perform a certain movement and acts on the patient's hand in order to perform the task.

Rehabilitation is a therapy which has the purpose to recover partially or totally the motor abilities of a patient. In the last years we assisted to an increasing demand of rehabilitation therapies, due to many factors such as the increasing of the average age of the population, the advancements in the treatment of pathologies that in the past were incurable and the increasing of activities with high risk of incidents or traumas.

Normally the motor deficits is caused by traumas like bone breaking or ligaments lesions, or to the natural degradation of the muscle-skeletal apparatus (due to the age). Also are increasing the pathologies of the nervous system. Belonging to this category are cranial traumas, Parkinson disease, spinal cord lesions, stroke.

For example, in the United States, stroke represents the main cause for the motor disability, approximately three million of persons have a permanent motor deficit due to this disease [1], [2].

Usually the rehabilitation therapy is based on the manipulation of the paretic limb supported by a specialized therapist. Depending on the subject, this procedure may be conducted with daily frequency for several months. It is clear that a big amounts of resources and time is required, both for the patient and the therapist. Furthermore the subject is forced to reach the clinic where the treatment is provided, with all the discomforts that this can produce. Another issue to take into account is the therapy cost, that usually is very high, indeed during the session the therapist is completely dedicated to a single patient.

In order to solve these problems, in the last decade, many laboratories involved in robotics and bioengineering have started projects with the main purpose to design and experiment automatic or semi-automatic systems for the hand rehabilitation. At the Rutgers University it was developed an haptic interface (Rutgers Master II) [3] that is able with four pneumatic actuators to flex the subject fingers with a maximum force of 16 N. Each actuator is equipped with a position sensor that allows to control the fingers closure by a computer interface and according to a specific training activity.

Another system, developed at the Center For Biomedical Engineering at University of California [4], is the Java Therapy-Joystick. This device uses a commercial force feedback joystick with a special game software, running on JVM (Java Virtual Machine). It is intended for the rehabilitation of hemiplegic stroke patients, and it can be used easily at home.

At MIT in the Newman Laboratory for Biomechanics and Human Rehabilitation, Krebs et al. [5] are working on a system that uses a robot manipulator in order to move the limb. This device was designed for the wrist rehabilitation and to have a low impedance to a free range of motion.

The device we developed in our laboratory (Artificial Intelligence and Robotics Laboratory, DEI, Politecnico di Milano) is born from our past experiences on an anthropomorphic artificial arm-hand [6], [7] and on a haptic interface for virtual reality applications [8].

In section two we draw the mechanical and electronic components of our system. Section three describes the EMG interface and how it is integrated into the system. Section four brings the preliminary results we have obtained testing the device. And finally section five outlines the conclusions and the future developments.

II. THE HAND REHABILITATION SYSTEM

As shown in fig. 1, the hand rehabilitation system we have implemented consists essentially of a PC (Personal Computer), a microcontroller, an actuated exoskeleton and a device for the recording of the myoelectric signals (EMG). The PC has three functions: it interacts with an operator (that can be the therapist or even the patient himself) by means of a graphic interface, it records and processes the myoelectric signals of the patient and finally it communicates with the microcontroller via serial connection to transmit commands

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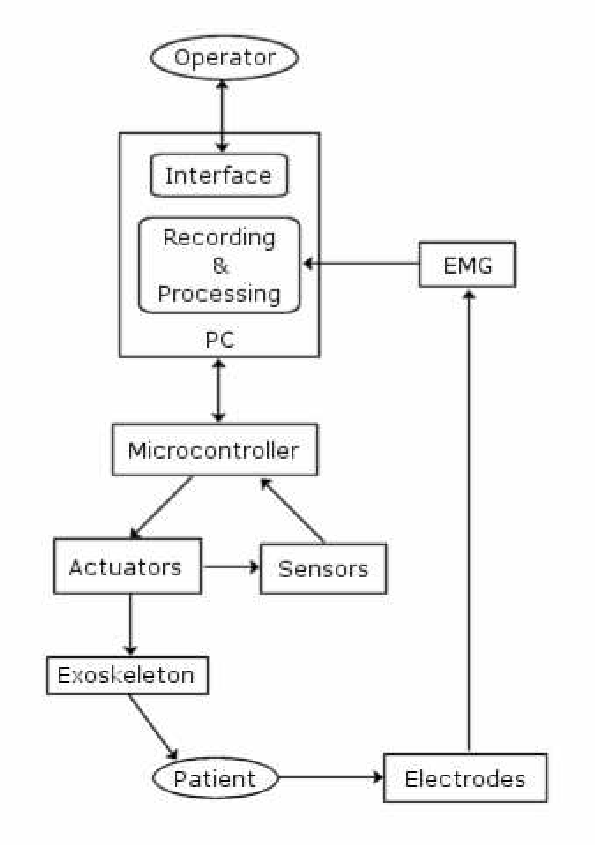


Fig. 1. Diagram of the hand rehabilitation system.

or to acquire sensory information. The microcontroller generates the command signals required to drive the actuators and controls their real positions by means of the sensors upon them. The actuators take effect on the exoskeleton that the patient has on. In fig. 2 the complete rehabilitation system is shown.

A. Exoskeleton

The exoskeleton we have realized is composed of a glove, upon which we have built a supporting structure, implemented in plastic. The plastic part on the glove is used for two reasons: guiding the fingers of the patient in order to accomplish a natural movement and avoiding that the fingers had to bear an excessive load on their tips. In addition to this, we have built two plastic bended covers that are placed upon and under the forearm of the patient and bound together by straps. In order to improve the system stability we have fastened the upper cover on the forearm with the plastic structure on the glove by means of a metallic bar.

On the upper cover (in the palmar side) we have fastened two actuators, that are Hitec servos HS-805BB. These electric motors can be controlled in position. Two wires are joined to the fingers tips at one end, and rolled up to the pulleys of the servos to the other end. The wires slide through some little plastic pipes and can transmit the maximum force produced by the actuators, about 100 N.

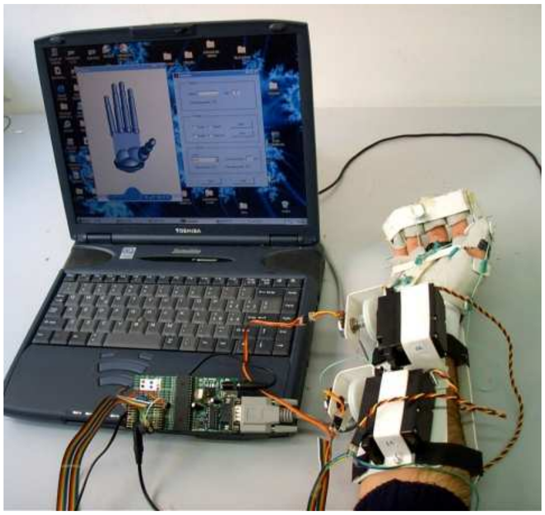


Fig. 2. Overview of the complete rehabilitation system.

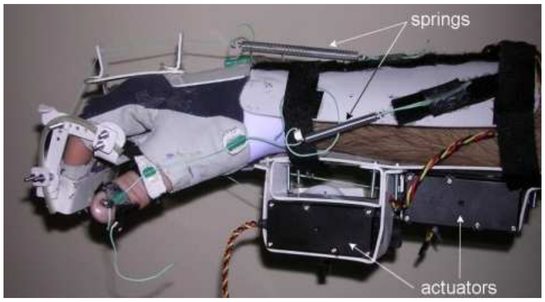
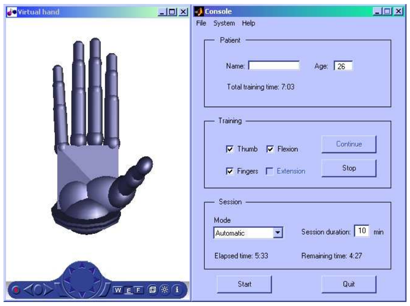


Fig. 3. Lateral view of the exoskeleton.

One wire is dedicated to the flexion of the thumb, while the other flexes the four fingers at the same time. On the dorsal side, two springs are required to allow the extension movements. In this way, with only two actuated degrees of freedom, the device is able to perform a grasp movement. Finally we have placed two potentiometers on the pulleys of the servos in order to record two position signals. We chose the potentiometers compared to other sensors for their low cost and good performance.

B. Electronics and Software

The interface between PC and the rehabilitation device is performed by a circuit board. A Microchip microcontroller (model 18F452) receives commands from the PC, generates the command signals for the two servos, and acquires analog signals from the potentiometers. It performs $8 \cdot 10^6$ operations per second, thanks to a 8 MHz quartz. The microcontroller transmits and receives data to and from the PC by a serial connection. It is programmed in C language and it avails itself of the Microchip MPLAB C libraries. A Matlab program implements the graphical interface (fig. 4), runs the recording and the processing of the EMG signals. The interface is composed of a virtual hand and of a console. The virtual



Patient

Name:
Age: 26
Total training time: 7:03

Training

☑ Thumb ☑ Flexion
☑ Fingers ☐ Extension

Session

Mode: Automatic
Session duration: 10 min
Elapsed time: 5:33
Remaining time: 4:27

Fig. 4. Virtual hand and therapy interface.

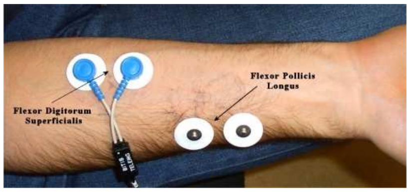


Fig. 5. Placement of the superficial electrodes.

hand is implemented in VRML (Virtual Reality Modelling Language) and animated by a Simulink program. During the therapy session: first the interface shows the hand movement that the patient should try to do, then glove performs the real movement. Using the console the therapist, or even the patient himself, can sets the rehabilitation session.

III. EMG Processing

In order to increase the effectiveness of the rehabilitation therapy, we used the myoelectric signals. The electric activity of the muscles allows us to know whether the patient is trying to move his fingers. In particular we are interested in EMG signals of the Flexor Digitorum Superficialis that flexes the four fingers together, and of the Flexor Pollicis Longus that allows the flexion of the thumb. Among all the numerous muscles that move the fingers, we chose these because they are much more involved in the grasp movement and because the electrodes for EMG recording can be placed on the forearm: in this way the recorded signals don't suffer from noise due to fingers movements. In fact both muscles are situated more or less in the middle of the forearm, in the ventral side. In this preliminary development phase of the device, we didn't take into consideration the muscles for fingers extension.

Fig. 5 shows where we placed the electrodes to record the muscular activity. The myoelectric signals were sampled at 500 Hz, rectified and then filtered according to the following equation:

$$s_j = \frac{1}{t_j - t_{j-K}} \sum_{i=j-K+1}^{j} |e_{i-1}|(t_i - t_{i-1}) \tag{1}$$

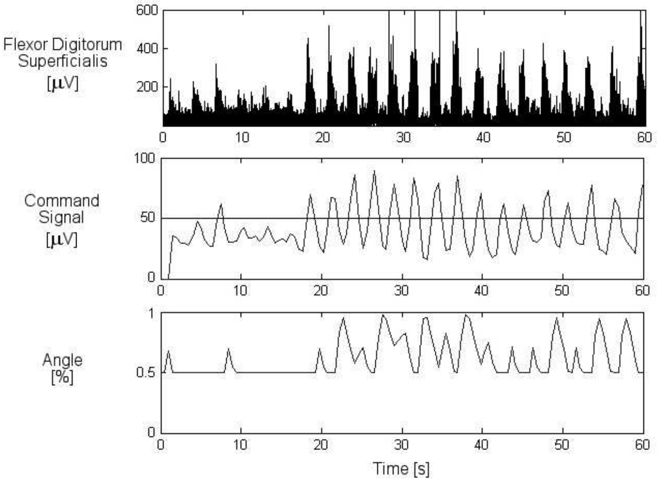


Fig. 6. a. Rectified EMG signal of Flexor Digitorum Superficialis b. Control signal c. Percentage rotation's angle of the servo pulley.

where s_j and e_j represent respectively the samples of the command signal used to control the actuators and of the myoelectric signal at time t_j and K is a parameter that defines the width of the sum operator's window.

IV. Preliminary Tests of the Device

In order to do a preliminary test of the system, we have recorded the myoelectric activity of a healthy 26 years old subject. In the first graph of fig. 6 the rectified signal relating to the contraction activity of Flexor Digitorum Superficialis is shown. This signal has been recorded while the subject performed three series of fingers movements within the interval of a minute. In the first 17 seconds only the thumb was periodically flexed. In the following 27 seconds the thumb remained in a relaxed condition and the subject performed the flexion of the other four fingers together. At the end of this test, all the fingers were simultaneously flexed as if they were performing a grasp movement.

It is important noticing the presence of cross-talk in the first part of the recording, that makes the signal more difficult to process. In the second graph of fig. 6 the command signal used to control the actuator is plotted. It was calculated according to the equation 1 with K equal to 500. The data have been processed by a computer equipped with an AMD Athlon processor at 1.1 GHz and 256 Mb of RAM.

In order to control the actuators we define a threshold σ. As it is possible to see in fig. 6, for this test we set σ equal to 50 μV. We defined this threshold in order to distinguish the real electric activity of the muscle from other interferences. In the last graph the rotation movements of the servomotor pulley are shown as they are recorded by the sensor. The rotation's angle is expressed in percentage: 0 means that fingers are extended, a value of 0.5 corresponds with a relaxed hand position, with the fingers lightly flexed and 1 denotes a totally closed hand. An actuator starts a flexion movement when its control signal exceeds the threshold: its speed v depends only on its current angle position ϑ and, at the time t, is calculated as:

$$v(t) = A \cdot (1 - \vartheta(t)) \tag{2}$$

where A is an opportunely chosen factor. In this way the motor speed is proportionally to the hand opening and progressively goes to zero while the fingers are flexing. The fingers return to their relaxed position when the correspondent control signal is less than the threshold. As it can be see, an appropriate choice of the threshold permits to filter most of the noise due to cross-talk, even if not totally.

However this control strategy is useful only in a more advanced phase of the therapy, when the patient is able to produce a significant amount of muscle activity, but he is not able yet to perform the movement by himself. As a matter of fact, in the first times, the rehabilitation system performs a very slow programmed movement, even if there aren't EMG signals recorded. Then the movement speed increases proportionally to the myoelectric activity of the patient.

In order to know whether it is possible to start a long term experimentation of our prototype, we have test it on a 65 years old hemiplegic female patient. The hemiplegia was caused by an ischemic stroke that occured a month before and that compromised also the patient's speaking ability. The exoskeleton didn't turn out to be easily wearable and the help of a qualified assistant is required to guarantee an optimal installation of the system. In particular we found that the adaptability of the plastic structure is hardly sufficient for the four fingers, whereas there were no problems for the thumb. The movements were performed without the EMG recording, therefore they were totally passive, that is under the control of the computer. We noticed that this particular implementation of the exoskeleton doesn't allow a very natural grasp movement: the flexion of the fingers should be coordinated in order to permit the opposition of the thumb. Moreover when an actuator flexes the four fingers together the rotations of the proximal interphalangeal joints are still much more remarkable than those of the metacarpophalangeal joints.

V. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

We have presented an exoskeleton for the rehabilitation of the hand: our main purpose was to build a device that helps patients to be more independent. In this way a single therapist can follow more than one patient at the same time, theoretically even at distance, if an Internet connection is available. Therefore we can reduce considerably the therapy costs and improve the rehabilitation service, because the patient will be able to train at home with a remote supervision. We have developed a very intuitive graphic interface, that even a not specialized person can use. The exoskeleton is designed to be adaptable and it is actuated by two servomotors. Two potentiometers are used as position sensors, in order to control the real status of the hand patient.

B. Future Works

Since we describe, with this paper, a first prototype there are many possible improvements that remain to do. With regard to the mechanical structure, it is desirable that the metacarpophalangeal joints have a greater range of motion and that the exoskeleton have a greater number of degrees of freedom. This means that more actuators are required than those used in this project. Nevertheless it may be necessary to use smaller servomotors, because those we used are too cumbersome and too powerful for our specific purpose. Moreover, although we have paid attention to build an adaptable exoskeleton as much as possible, a more complex structure may turn out more functional and more easily wearable by a patient.

It is also important developing more advanced technics for the EMG processing, that taking into account the natural variability of these signals. For this purpose the recording of the myoelectric activity from other sites can turn out useful. Besides a methodology to measure patient improvements is missing. This is particularly important because it may be a considerable motivational factor.

Finally it is necessary to program a test series with several patients in order to prove the real effectiveness of the hand rehabilitation system we have developed.

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