Exoskeletons for Rehabilitation and Motor Control

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***Abstract* – Exoskeletons are mechatronic systems worn by a person in such a way that the physical interface permits a direct transfer of mechanical power and exchange of information. These robotic mechanisms have been applied in telemanipulation, man-amplifier, rehabilitation and to assist impaired human motor control. In addition, the neuromotor control research can benefit from a exoskeleton in order to manipulate human arm movements within its natural workspace, which is not possible with traditional robotic manipulandum because of its constraints.**

The aim of this paper is to describe a set of experiments in motor control and the application of powered upper limb exoskeleton in which the mechanical requirements of the movement will be modified, e.g. removal of the interaction torques in order to identify their impact on the production of complex coordination patterns in healthy subjects with the possibility for a future application to neurologically impaired subjects. As preliminary results, are shown responses to changes in viscosity and inertia when external perturbations (viscous load and inertia) are applied during execution of elbow angular cyclical movements using a robotic exoskeleton.

***Index Terms* – Exoskeletons, rehabilitation robotics, motor control, orthotics.**

I. INTRODUCTION

The scientific and medical community is becoming more and more interested in the so-called Rehabilitation Robotics. Rehabilitation Robotics has been envisioned as technology for the restoration and functional compensation of people suffering from physical disability or disorders, either for the rehabilitation therapy or assistance of people.

In robotic field, exoskeletons are mechatronic devices of which segments and joints correspond to some extend to these of the human body and the system is externally coupled to the person ("wearable" robot). The primary applications of exoskeletons were teleoperation and power amplification. Later, exoskeletons have been considered as devices for rehabilitation and assistance of disabled or elderly people by means of upper and/or lower limb orthosis. Lastly, taking into account that robotic exoskeletons are able to apply independent dynamic forces on human joints and segments, these devices permits to realize experiments and studies on motor control, adaptation and neuro-motor research.

In rehabilitation applications, the exoskeleton should be able to replicate with a patient the movements performed with a therapist during the treatment. In addition, the sensors attached to the exoskeleton can assess forces and movements of the patient. This would give to the therapist quantitative feedback on the recovery of the patients and would imply a more efficient rehabilitation process. Therefore, the exoskeleton could act as tool for the measurement of the performance and the evolution of the treatment. For instance, in Reference [1] was presented a robotic device based on impedance control to guide patient's movements in specified trajectories and was demonstrated the beneficial effects of the treatment.

In the case of exoskeletons for human performance amplification or functional compensation, the patient provides control signals to the device, while the exoskeleton provides most of the mechanical power required to carry out the task. The human becomes a part of the system and feels a scaled-down version of the external load carried by the device due to the force reflection [2]. Most of the developments have focused on the upper and lower limb. In general, rehabilitation robots can be classified, see [3], under three categories:

1) Posture support mechanisms.
2) Rehabilitation mechanisms.
3) Robots to assist or replace body functions.

One important and specific aspect in Rehabilitation Robotics is the intrinsic interaction between human and robot. This interaction is twofold. First, cognitive, because the human controls the robot while it provides feedback to the human; second, a biomechanical interaction leading to the application of controlled forces between both actors. In Reference [2] it was discussed mechanism and control for power assist robotic arms defined as "extenders" and it was analysed the dynamics of human-machine interaction in sense of the transfer of power and information signals.

There is a physical interface between person and device to provide the mechanical power. Concerns of this physical interface are safety, robustness and reliability of the robotic mechanism taking into account the characteristics of the human neuromuscular-skeletal system. A relevant aspect in the interface to assist impaired human motor control is the information (control signal) required of voluntary motor control which may be provided using several channels and methods, for instance: measurement of movement, interface forces with the device, muscles activation, brain activity. The channel used will depend on the specific application and availability.

A typical example of this cognitive interaction is the one being developed through the EMG control of artificial robotics prostheses (see Fig. 1), [4]. Here, the human myoelectrical signals are used to generate control commands to drive an intelligent prosthesis. Force feedback can be implemented in several ways. On the other hand, an example of biomechanical interaction is found in exoskeleton based functional compensation of human gait. In this case the robotic exoskeleton applies functional compensation by supporting human gait, i.e. by stabilizing the stance phase [5].

This paper presents a survey of exoskeletons focused on rehabilitation and assistance of disabled persons. In addition, a set of motor control experiments performed with an robotic exoskeleton illustrate the application of these devices to motor control research. The inertia and viscosity of the human arm were modified by means of a upper limb exoskeleton in a series of cyclical elbow flexo-extensions. A historical perspective of developments realized up to now is presented in section II. In section III it will be presented a detailed study of the trends and emerging technologies in measurement, actuation and control that will be applied in next developments to overcome the actual limitations. This will be followed by a description of experiments carry out with the robotic exoskeleton at the elbow level. Finally, the conclusions and future research is discussed.

II. EXOSKELETONS FOR UPPER LIMB

The earliest applications of exoskeleton arms were in the field of telemanipulation with several outstanding developments. A illustrative example is the "Exoskeleton Force ArmMaster" developed by Exos corporation with five motorized DOF for shoulder and elbow joints. The system is completely backmounted and can exert a torque able to go from 13Nm on the forearm to 40Nm on the arm. Other exoskeletal robotic structure was developed by the Bergamasco team, [6], and it has 7 DOF corresponding to human arm articulations from the shoulder to the wrist. The weight of the device was over 10 kilograms.

The main drawback of these earlier structures is that the total weight was high. In line with the developments of new technologies, the structures of the exoskeletons become lighter, allowing the application of exoskeletons in the rehabilitation field in ambulatory conditions, for instance, in the restoration and maintenance of motor functions.

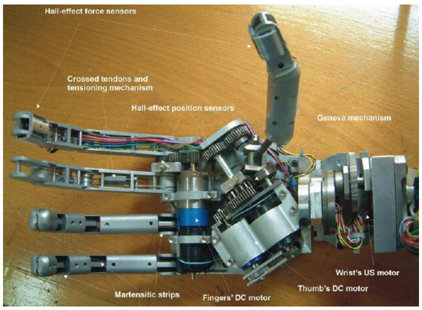

Fig. 1 Prosthetic hand (Manus project) controlled by EMG.

Several studies have suggested that repetitive training is helpful for upper limb functional recovery. The robotic exoskeletons could provide the repetitive training and has been applied for post-stroke people. In addition, exoskeletons could help to carry out activities of daily living of persons with motor disorders, weakness, spinal cord injuries and other pathologies.

A 8 DOF robotic device to help forearm motion was presented in [7]. It was implemented with DC servo motors and the control was based on kinematics and dynamics information. Great attention was paid to all aspects of safety. This orthosis is a non-ambulatory device since it must to be anchored to a base.

MULOS (motorized upper limb orthosis system), [8], is a 5 DOF electrically powered exoskeleton. It has 3 DOF at shoulder level, 1 at elbow and 1 to provide pronation/supination. The MULOS system was designed to operate under three modes of control: Assistive, Continues Passive Motion and Exercise. The prototype orthosis was wheelchair-mounted.

Was developed in [9] a 3 DOF exoskeleton to assist upper limb motion. This device was designed to help physically weakness patients such as ancients, disabled and injury people. The device was activated by DC motors and it was controlled by means of EMG signals and kinematics variables.

Rosen constructed an exoskeletal system based on myoelectric signals. The main objective of this system was to study the interaction between the upper arm and the exoskeleton. The device amplifies the moment generated by the arm muscles related to the elbow flexo-extension movement, [10]. It was powered by DC motors and it was controlled by dynamics, kinematics and neuro-muscular (EMG) information. The mechanism is externally referenced since it has to be fixed to a wall.

The work in [11] has focused on developing a exoskeleton with 7 DOF for rehabilitation and training of upper arm. The device was very light since it was activated by pneumatic actuators (pMA - pneumatic Muscle Actuators). Each joint was individually controlled by a torque control strategy.

A hand exoskeleton was constructed and presented in [12]. It was controlled by means of EMG signals and was based on pneumatic actuation. Several algorithms and strategies to control the device were compared with a quadriplegic patient in pinching motion between the index finger and the thumb.

With respect to the use of EEG (electro-encephalography signals) as control information, in [13] was presented a set of experiments to investigate the control of a hand orthosis by means of EEG-based Brain-Computer Interface (BCI). The orthosis was opened and closed with the EEG signals resulting from the imagination of different motor actions. The main drawback was the long training period for a patient to generate a command. In addition, the effectiveness of the system was not complete.

WOTAS (Wearable Orthosis for Tremor Assessment and Suppression) is an exoskeleton designed for the upper limb. It was implemented for functional compensation of handicapped people with movements disorders such as tremor [14]. This device used traditional actuation technologies (DC and ultrasonic motors) and the total weight of the final system is roughly 850 g (see Fig. 2). The control was realized through impedance control. This system was a platform to test non-grounded tremor reduction strategies by applying biomechanical loading on tremorous movement. The Section IV presents a application of this robotic device in the neuromotor research field.

Nowadays, there are several projects around of the world aimed at developing robotic exoskeletons, most of them for the upper limb [15], [16]. The challenge for these developments is to produce useful for selected applications exoskeletons commercially available.

III. TECHNOLOGIES IN EXOSKELETONS

A. Sensors

The feedback information provided by sensors mounted on exoskeletons may include kinematics, kinetic and physiological (EMG, EEG) measurements, taking into account the control algorithm to be used. In kinematics measures there are several options, such as potentiometers, Hall effect sensors, optical encoders, accelerometers, gyroscopes, electrogoniometers and cable tension sensors.

In this field, the MEMS (microelectromechanical systems) have evolved with interesting developments in size, frequency response, range, reliability, wearability and integral electronics. The inertial sensors using this technology are particularly important for kinematics measurements in robotic mechanisms.

The robotic devices using EMG sensors to measure muscle activity are widely implemented with surface sensors. The information obtained reflects the forces that will be generated by the muscles before the mechanical contractions and may be just used by the controller of an exoskeleton to detect intention of users. For instance, a myoprocessor based in Hill Model was presented in [17] to control an exoskeleton using the neural activation information.

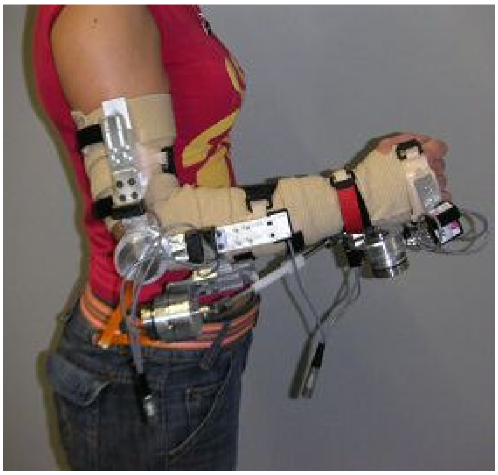

Fig. 2 WOTAS exoskeleton to assist upper limb.

The devices using non-muscular information channels such as BCI to command exoskeletons are still experimental. Bioelectrical brain activity may be obtained using sensors in invasive and non-invasive ways, such as EEG, ECoG and intracortial. EEG signals were used in the prototype described in [18].

Several researches are directed toward bio-inspired sensing, to take advantage of features of biological transducers, [19].

B. Actuators

In literature, the majority of developments of exoskeletons have been implemented using DC motors for actuation [10], [14], [20] due to its precise control (velocity and torque). In addition, it is a very well-known technology. Several devices studied were activated by pneumatic actuators, [12], due to its power-to-weight ratio. The main limitations of exoskeletons as permanent assistive devices are, the energy density provided by the actuators. It must be high, specially for the lower limb and the energy storage devices which must provide autonomy for several hours. Therefore, when developing portable exoskeletons a tradeoff between power and weight must be considered.

Lately, several devices have been built using the so-called emerging actuator technologies, though these experimental actuators continue in investigation [11], [21]. Among the actuators under development, [22], the electroactive polymers and artificial muscles are a promising technology to be used, because of the high power delivery and low mass. Their mechanical properties has been widely studied recently and McKibben actuators [23] are currently used in biomimetic robots. These actuators may become relevant to provide mechanical power in exoskeletons due to the advantages of light weight and good power-to-weight ratio. On the other hand, the control is very difficult due to their nonlinear response and hysteresis.

Series Elastic Actuators provide benefits in force control of robots and some exoskeletons incorporating them [24], [25] as well as biomimetic legged robots have been built. These benefits include high force fidelity, low impedance, low friction and good force control bandwidth.

C. Control

Few years ago the control in robotic exoskeletons was realized using kinematics commands or dynamics commands [11], [14]. Later, a new technology in control using neuro-muscular signals such as the electromyography (EMG) was implemented in several prototypes of robotic exoskeletons [9], [10], [12]. The control based in EMG signal permits a deeper integration with the device. However there are problems such as interference in the muscle activation level, noise and dependence of multiple muscles.

There are other channels that might provide information to determine the intention such as measurements of brain activity or brain-computer interface (BCI) for those with severe neuromuscular disorders and those who lack of muscle control.

Several methods to obtain brain signals might be used such as electro-encephalography (EEG), magneto-encephalography (MEG) and magnetic resonance imaging (fMRI). MEG, PET and fMRI are not convenient for be used as control of external devices [26], because of the technical cost.

The EEG has been recently used to command neuroprosthesis and orthotic devices [18], [27]. Taking into account the correlations between EEG signals and actual or imagined movements and between EEG signal and mental tasks it is possible to extract control features to command those devices. This will become specially important for paraplegic patients without residual signals. Nevertheless, this demand many technological considerations to create practical and feasible devices.

The control of exoskeletons as assistance tool requires special considerations such as robustness, reliability and safe taking into account that device must identify the intention of user, analyze the information in real-time and compute the mechanical power to release in the right instant.

IV. UPPER LIMB EXOSKELETON APPLICATION

As was presented in [14], the WOTAS wearability during daily living activities was evaluated in the laboratory while the subject executed a wide variety of tasks without any actuation on the arm. These preliminary tests showed that the system did not affect the normal range of motion of the user [14]. In a second stage, the system was used to evaluate and remove tremor in different patients. The patients wore WOTAS while it applied a passive control strategy (adding viscosity and inertia to the tremorous movement) [14]. The system was able to measure and estimate tremor parameters.

The capacity of applying dynamic internal forces to the upper limb for tremor suppression was also evaluated and it was found that the device could achieve a consistent 30% of tremor power reduction, being able to attain reduction ratio in the order of 80% in the tremor power for patients with severe tremor (see Fig. 3, corresponding to a patient suffering essential tremor).

The powered exoskeleton WOTAS has some possible application in neuro-motor research [28], [29]. The device provides a way of manipulating the mechanical conditions (viscous and inertial) of each joint independently since the mechanical loads are applied by the exoskeleton directly to the arm and forearm. The sensors on WOTAS measure the kinematic and kinetics of the arm (currently, including wrist and elbow) that allow to define coordinated limb movements, multi-joint motor tasks and several postures under various mechanical conditions.

A set of behavioral experiments are currently being conducted to address the effect of mechanical interactions (external and internal forces) on the upper limb control strategies, including the modification of the interaction torques during reaching and cyclical coordination tasks with the powered arm orthosis.

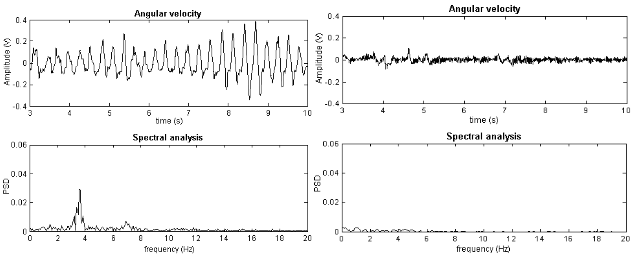

Fig. 3 Example of tremor suppression. Movement in free mode (left) and when exoskeleton applied an viscosity at the elbow joint of 0.3 N.m.s/rad to the tremorous motion of patient (right).

In a preliminary set of tests, the viscosity and inertia at the elbow joint were modified during the execution of cyclical elbow flexion and extension at a paced rhythm of 1 s. The subjects wore a robotic exoskeleton (WOTAS) on its right (dominate) arm that permitted flexion and extension motion of the elbow joint in the vertical plane. Shaft joint on the device was aligned with subject elbow joint, and the device was attached to its upper arm and forearm. The subject wearing the exoskeleton executed elbow angular cyclical movements while the elbow position, joint angular velocity, force and EMG from biceps and triceps were recorded. Data were sampled at 1 KHz and each trial lasted 20 seconds.

During the execution of movements, mechanical perturbations were applied to the elbow joint. These perturbations are manipulated applying viscous resistance and inertial load at the elbow joint level at specific instants. The subject was instructed to maintain the same speed and frequency independently of loads. The magnitude of mechanical perturbations were 0.4 N.m.s/rad for viscous load and 0.3 N.m.s^2/rad for inertial load.

It was expected that changes in the viscosity would cause larger changes in joint motion than changes in inertia, because variations in inertia are very frequent in daily life, while changes in viscosity would be more difficult to find during normal activities. The preliminary results are shown in Fig. 4 and 5. These figures presents the elbow joint angular velocity in rad/s (upper) and the rectified and filtered (low-pass 4th order Butterworth, recursive) Biceps EMG (lower), during the execution of cyclical elbow flexo-extensions. Response to a change in viscosity is shown in Fig. 4 and to a change in inertia is shown in Fig 5. The overshoot after the removal of the viscosity (Fig. 4), indicates that these experiments can be used to confirm our hypothesis.

V. DISCUSSION AND FUTURE RESEARCH

At this moment, it is intended to design and implement the arm control strategies to remove artificially the effect of the distal segment interaction torques, such as torques in the proximal joint resulting from the accelerations of the distal joint. It is hypothesized that removing the interaction torques in healthy subjects will shift the muscle patterns to a pure joint acceleration and deceleration control strategy while in impaired subjects (e.g. cerebellar injury) this will lead to decreased movement errors both in target and intralimb coordination [30], [31].

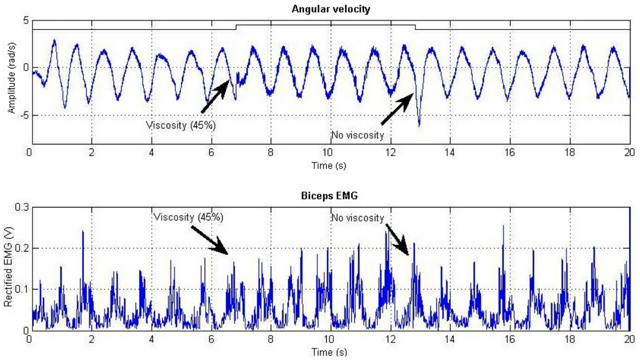

Fig. 4 Response to a change in viscosity (see trace in black).

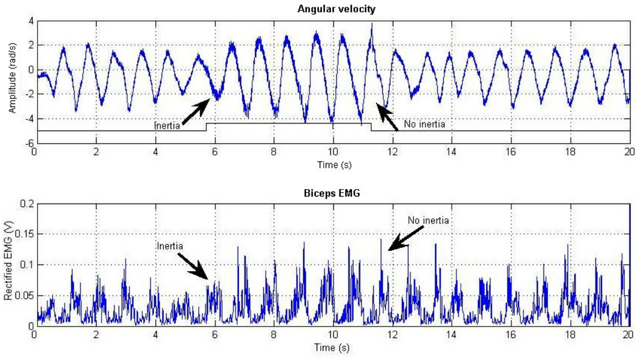

Fig. 5 Response to a change in inertia (see trace in black).

The experiments consist of:

1) Goal-directed motion -reaching-
2) Coordination patterns involving elbows and wrists -cyclical coordination task- [32]

It is expected that these experiments will reveal the role of the interaction and muscular torques in constraining inter and intra-limb coordination in healthy subjects. Also are being conducted studies to investigate the mechanisms and strategies in adaptation and compensation for loads during elbow and wrist movements.

Current trends in exoskeletons as assistive devices are directed towards optimizing the actuation components by integrating new materials and different technologies (mainly the artificial muscles), as well as the development of advanced control strategies to process the physiological signals such as EMG and EEG directed to predict the intention of the user.

The powered exoskeletons for rehabilitation can be implemented with the current technology in measurement, actuation and control, if the therapy is confined to a hospital. The challenges in this application are directed toward exploring ways in which the exoskeletons can facilitate new therapies that cannot be applied by a human therapist. These robotic devices are able to provide precise perturbation profiles to help patients relearn specific target movements, as described in [33].

An important topic of research is to identify in which way robotic exoskeletons may provide optimum therapy from different points of view, such as intensity, patterns of exercise and motor training. The Gentle/s project [34] investigated the neuro-rehabilitation of CVA (Cerebral Vascular Accident) patients. It was aimed at evaluating robot therapy and developing new therapies to aid the increase of relearning stimulation in the brain. The patients were encouraged to move a robotic arm (HapticMaster) which rendered a virtual environment that included inertia, stiffness and damping.

Currently, the NeuroRobotics project [35] focus on the design, development and testing of wearable or tele-operated robotic systems, controlled by the human operator. The project integrates several fields from neuroscience to robotics. Several hybrid platforms featuring different levels of interface (mechanical coupling with the human body) and of connectivity (to the human nervous system) are currently under development to be used in experiments on human augmentation.

VI. CONCLUSIONS

Motor disorders, physical weakness and other disabilities regarding motion have a great impact on the quality of life of people suffering from them, particularly in the activities of the daily living (ADL). There is a lot of interest on developing robotic mechanisms worn by humans (exoskeletons) as alternative to help these patients. In addition, these devices not only benefit from motor control research field, but also contribute to its development. Its workspace and DOFs close to human joints permit that perturbations can be applied on each joint using robotic exoskeletons.

The capacity of applying dynamic forces to the body and specifically to upper and lower limb opens the application field of exoskeletons. They could be applied in different areas of the rehabilitation robotics, for instance, it could provide restoration or maintenance of motor function to different joints on the limbs. Most of the powered orthosis designed in this area are non-ambulatory devices and there is a need in the rehabilitation area of ambulatory devices able to apply dynamic forces.

Several challenges remain and advances in actuation and energy storage technologies are required before exoskeletons see widespread use to assist impaired human motor control. When developing portable exoskeletons a tradeoff between power and weight must be considered. Most of the devices presented were tested on human subjects, but they did not prove to be useful enough to be applied at wider scale. Therefore, it is needed to develop exoskeletons which are commercially available.

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