Wearable Robots in Rehabilitation Engineering Tremor Suppression

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1. Introduction

Wearable robots (Soft robots) are person-oriented robots. They can be defined as those worn by human operators, whether to supplement the function of a limb or to replace it completely. Wearable robots may operate alongside human limbs, as in the case of orthotic robots or exoskeletons, or they may substitute for missing limbs, for instance following an amputation. Wearable Robots have been proposed in the context of rehabilitation, but practical implementation of these rehabilitation robots is strongly limited by available actuator and sensor technologies. In most instances technologies are the limiting factor in developing novel robots. This is also true of wearable robots. Wearable robots are in many cases related to portable and ambulatory applications; however, only a few examples of fully portable wearable robots can be found in the literature, one reason being a lack of enabling technologies.

Ambulatory scenarios require compact, miniaturized, energetically efficient technologies, e.g. control, sensors, actuators. All technologies involved in robotics need further development, but actuators and power sources are the ones that probably most limit wearability and portability at the present time while sensors are the ones most limiting efficient implementation of cHRI (Pons, 2005).

Portability is one important aspect of wearable robotics, but the distinctive characteristic of wearable robots is dual cognitive and physical interaction with the human wearer. This immediately raises dependability and safety issues in robotics. Dependability and safety ultimately have a close bearing on control, sensor and actuator technologies. In the area of Rehabilitation WRs, the key idea is empowering a weak musculo-skeletal system or a person with deficient motor control.

It is clear that the design of wearable robots can benefit from biological models in a number of aspects like control, sensing and actuation. Likewise, wearable robots can be used to understand and formalize models of biological motor control in humans.

This book chapter aims to analyse these issues in the framework of tremor suppression. First, the chapter will introduce the work performed by authors in the development and validation of an upper limb exoskeleton for tremor suppression called WOTAS (wearable orthosis for tremor assessment and suppression). It will describe in detail the general concept for WOTAS, outlining the special features of the design and selection of system components. A control strategy developed for tremor suppression based on the exoskeletons will be described. Results from experiments using these two strategies on patients with tremor will be summarized. Finally, results from clinical trials will be presented. Results indicate that the exoskeleton is able to attain a reduction ratio in the order of 80% tremor power in specific joints of patients with severe tremor. Robotics based solutions have shown clinical evidence of the approach based on human limb impedance control. However it results in bulky and non-cosmetic solutions for which patients are especially reluctant, (Rocon et al., 2007).

At the end, the chapter will describe the work being performed in the framework of TREMOR project that tries to overcome these limitations by exploring the so-called enabling technologies. TREMOR project is focused on the development of a new methodology for Functional Electrical Stimulation, FES, based on addressable arrays of electrodes, which overcome the limitations of actual electrodes for functional stimulation, therefore FES is proposed as an alternative actuation technology for this sort of robots. Moreover, the chapter will evaluate the application of inertial sensors (Inertial Measurement Units, IMU) as sensing technologies in controlled wearable/soft robots.

2. Tremor suppression by means of an upper limb exoskeleton

Tremor is defined as a rhythmic oscillatory activity of body parts (Findley and Koller 1995). The oscillatory activities are related to various combinations of four basic mechanisms: (a) mechanically-induced oscillations, (b) oscillations due to reflexes, (c) oscillations generated by neuronal generators in the central nervous system, (d) oscillations resulting from impaired feedforward and feedback loops (Deuschl et al. 2001). Tremor amplitude tends to increase and progress more medially (from distal to proximal joints) over time, while tremor frequency tends to be inversely related to age (Rajput et al. 2004). More than 90 % of patients who come to medical attention report disability (Louis 2005). For instance, Essential Tremor (ET) affects approximately 4 % of the population above 65 years of age, representing the most common movement disorder in the elderly (Benito-Leon et al. 2003; Louis et al. 2005; Thanvi et al. 2006).

Current strategies in the treatment of tremor are based on drugs (mainly the front-line agents primidone and propranolol), and surgery (thalamotomy and deep brain stimulation) in those patients being refractory to drugs (Louis 2005; Ushe et al. 2004). Gamma knife thalamotomy could represent an option for difficult cases (Niranjan et al. 2000; Young et al. 2000). However, (a) tremor is not managed effectively or sufficiently in about 25 % of patients, (b) the drugs used often induce side effects, may be contra-indicated or do present potential side effects or contra-indications which make their use more difficult, and (c) surgery is associated with a risk of hemorrhage and psychiatric manifestations (Binder et al. 2003). Moreover, a high rate of suicide (4.3 %) has been found recently in patients treated with deep brain stimulation (Burkhard et al. 2004). Therefore, further research and new therapeutic options are required to manage tremor most effectively.

2.1 Wearable orthosis for tremor assessment and suppression

The effects of load and force on tremor have received considerable attention by the research community. Amongst others, Adelstein (Adeltein 1981), has conducted a thorough analysis of the effect of viscous loading as a means for active reduction of intention tremor. As a result, Adelstein reports that significant and steady reductions of tremor amplitude are observed as the viscous loading increase. This phenomenon gives rise to the possibility of an orthotic management of tremor. An orthosis is defined as a medical device that acts in parallel to a segment of the body in order to compensate some dysfunction. In the case of tremor management, the orthosis must apply a damping or inertial load to a selected set of limb articulations. As a wearable device, it must exhibit a number of aesthetics, cosmetic as well as functional characteristics. Aesthetics and cosmetics are more directly related to size, weight and appearance of the orthosis. Functionality is more related to the trade-off required in terms of required torque and velocity and to the robustness of operation.

This section presents the active orthosis (exoskeleton) WOTAS, which is able to apply effective viscosity and/or inertia attached to the upper limb of the patient (Figure 1). This active orthosis is designed after the shape and function of the human upper limb, segments and joints correspond to some extent to these of the human body while the system is externally coupled to the person. The exoskeleton activates the elbow and wrist joints, being able to measure and apply forces on three movements of the upper limb: elbow flexion-extension, forearm pronation-supination and wrist flexion-extension. WOTAS is activated by a set of rotary flat DC motors (EC 45 Flat Brushless DC motor, Maxon Inc.) and harmonic pancake transmissions (Rocon et al., 2007). This solution was selected based on a comparison of available technologies for actuation and represent a compact and light solution suitable for wearable devices.

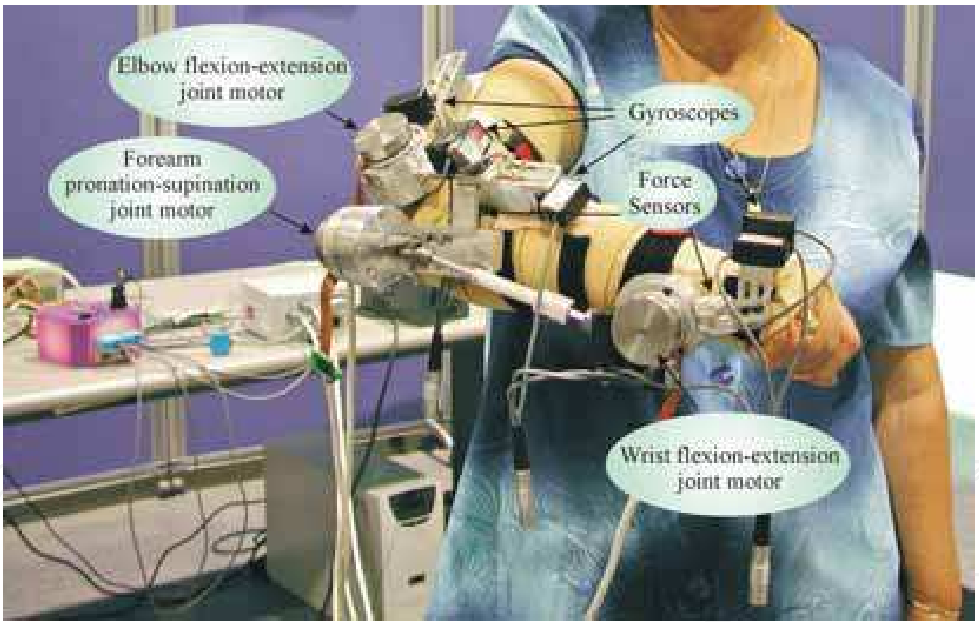

Fig. 1. Patient using the WOTAS orthosis affixed on the right upper limb. This robotic device spans the elbow and wrist joints, being able to apply independent tremor suppression strategies to elbow flexo-extension, wrist flexo-extension and wrist prono-supination.

The mechanical design of the exoskeleton elbow joint is based on a hinge joint with the axis of rotation placed in the line between the two epycondyles. The actuator solution adopted is attached to the structure with its rotary axis aligned with the elbow joint of the exoskeleton. The wrist joint adopted the same solution but with the axis of rotation placed in the line between the capitate and lunate bones of the carpus. The solution developed for the control of pronation-supination movement is novel and based on controlling the rotation of a bar placed parallel to the forearm, see Figure 1. The total weight of the final system is roughly 850 gr.

The active orthosis developed aims at allowing both monitoring of upper limb movements and implementation of tremor suppression strategies. Therefore, it is equipped with kinematics (angular velocity) and kinetic (interaction force between limb and orthosis) sensors. The rate of rotation of each activated joint is detected by sensor system based on a combination of two independent chip gyroscopes (ENC-03J manufactured by Murata Inc.), placed distally and proximally to each activated joint. Angular position and acceleration information are obtained through mathematical operations. The interaction force between the exoskeleton and the user is measured by a force sensor based on strain gauges (Rocon et al., 2007).

Other important aspect of the design of active orthoses that will apply dynamic force between segments of the human limbs is the transmission of load through the soft tissues to the human skeleton. In order to minimize this difficulty, the WOTAS orthosis is adaptable to each configuration of the joint among different patients owing to the use of thermoplastics, see Figure 1. In addition, a textile substrate was used to compress the soft tissues and enhance performance of the fixation supports.

The active orthosis is controlled by a computer with a dedicated software application that implements an algorithm able to distinguish in real time tremorous from voluntary movement at joint level, and to calculate the force to be applied by the active orthosis on the upper limb in order to change its biomechanical characteristics and, consequently, suppress tremor. In summary, the control system works as follow:

1. the sensors coupled to the limb measure its motion,
2. an error cancelling algorithm performs a real-time discrimination of the undesired component of motion,
3. tremor information is sent as the input to the controller in order to generate the desired exoskeleton actuation to suppress the tremor (see Figure 2a).

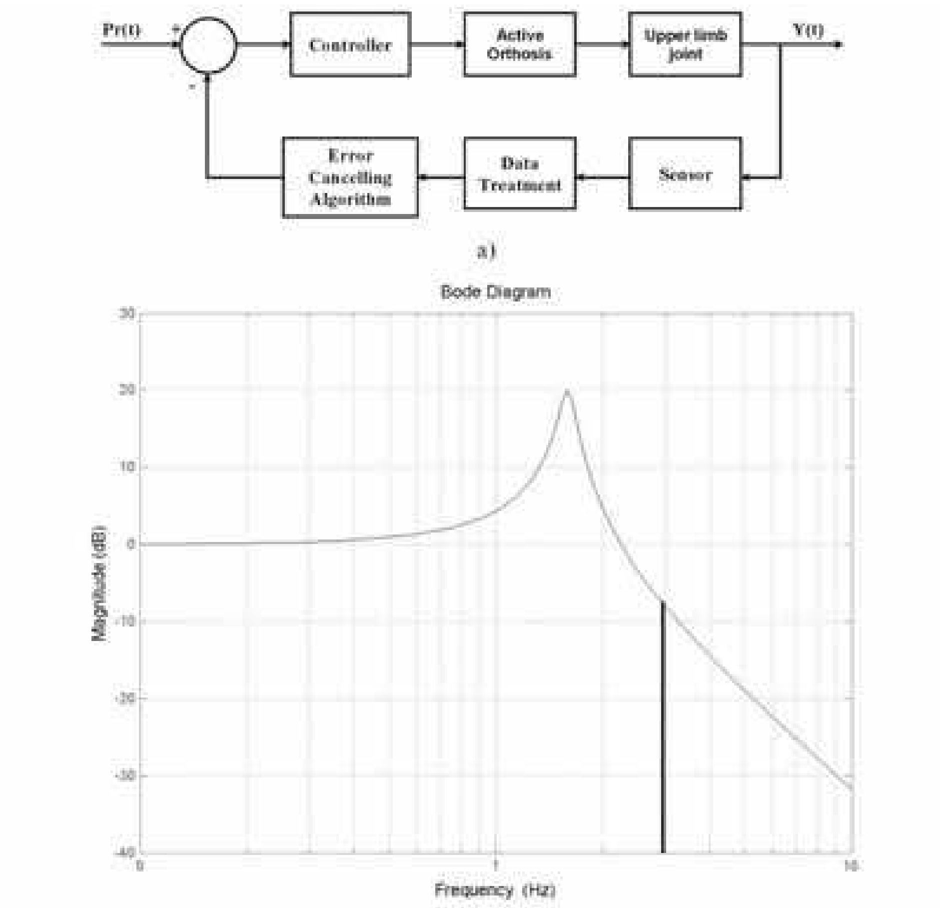

Fig. 2. a) Tremor suppression control system. The movement of each upper limb joint is detected by gyroscopes. An error cancelling algorithm performs a real-time discrimination of the tremorous (undesired) component of motion. The angular velocity information from the estimated tremorous component is used to calculate the reference mass and damping characteristics of the upper limb. This process estimates the actual impedance force of the system, defining the apparent impedance of the upper limb and consequently reducing the tremor. b) The musculo-skeletal system is modelled as a second order biomechanical system. The active orthosis is used to modify the apparent biomechanical characteristics of the upper limb so that the cut-off frequency, fc, lies between the frequency range of voluntary and tremor motion.

In this approach, the musculo-skeletal system (each upper-limb joint contributing to tremor) is modelled as a second order biomechanical system exhibiting a low-pass filtering behaviour. The cut-off frequency of this second order system is directly related to the biomechanical parameters of the second order system, i.e. inertia, damping and stiffness. Our approach consists in selecting the appropriate modified values of inertia and damping of the musculo-skeletal system, so that the cut-off frequency lies immediately above the maximum frequency of the voluntary motion and well below the tremor frequency, see Figure 2b.

For a successful active tremor absorption mechanism, a means for intelligent detection of tremor vs. voluntary motion is required. To this end, a model of the tremor motion is proposed. The algorithm developed is based on a two-stage method that estimates voluntary and tremorous motion with a small phase lag (Rocon et al., 2007). It is based on the fact that the the voluntary motion of activities of daily living, ADL, occurs at frequencies lower than the tremorous movements (Riviere, 1995). Based on this, in the first stage of the algorithm, the voluntary motion is estimated using a Benedict-Bordner filter tuned to estimate low frequency movements. In the second stage, the estimated voluntary motion is removed from the overall motion and it is assumed that the remaining movement is tremor. Next, an adaptive algorithm estimates tremor using a sinusoidal model, estimating its time-varying frequency, amplitude and phase (Riviere, 1995). This algorithm was evaluated with 33 subjects presenting different tremor diseases. Results demonstrated the correct operation of the algorithm, being able to estimate with a small phase lag (roughly 1 ms of time delay introduced) the voluntary and tremor components from the overall movement.

2.2 Experimental protocol

The performance of the WOTAS active orthosis was evaluated in an experimental phase involving six patient suffering from Essential tremor (3 female; 3 male; mean age 72,3 +/- 4.3 years). These patients were exhibiting a bilateral postural/kinetic tremor in upper limbs at intensities of 2/4 to 4/4 despite regular intake of medication (primidone up to/day 500 mg, propranolol up to 160 mg/day, or a combination of both), in agreement with the criteria of ET (consensus statement of the MDS). Regular anti-tremor medications were maintained stable during the week preceding the assessment. The investigation was approved by the ethical committee and patients gave their written informed consent.

The effects of biomechanical loading were investigated for the upper limb on one side during the execution of the different clinical tasks (keep the upper limbs outstretched in a horizontal position, point the nose with the index starting from the thigh, and keep the arm in a rest position over the thigh). These tasks have been previously used to characterise tremor movement (Belda-Lois et al., 2004).

During the experiments, WOTAS operated basically in two different control modes:

1. Monitoring mode: WOTAS operates in free mode (no force is applied on the upper limb) and monitor tremor parameters of the patients.
2. Suppression mode: WOTAS is able to change biomechanical characteristics of upper limb, such as viscosity or inertia, in order to suppress tremor.

The order in which the modes have been applied has been alternated, as well as the order in which the patients have executed the tasks. This approach was adopted in order to avoid interactions in the analysis, as well as learning effects (Belda et al., 2004). During the experiments the patient did not know when the system were applying a suppressing strategy or when it was operating in monitoring mode. Just the computer operator knew when the systems were applying the suppression strategy. For formal purposes, we consider this arrangement equivalent to a double-blind trial in order to reduce the placebo effects in the experimentation phase (Belda et al., 2004).

The figure of merit adopted to quantify the reduction achieved by the active orthosis is the ratio between the signal analysed in monitoring mode, and the signal analysed in suppression mode. Therefore, the reduction of tremor was measured with the patients under the same conditions: with the orthosis placed on the upper limb.

2.3 Results

The effects of adding effective biomechanical loading were investigated for the upper limb during the execution of the different clinical tasks. During the trials, some patients were able to identify when the system was operating in suppression mode, relating to the clinician either 'now the system is suppressing my tremor' or 'now it is not'.

According to the results, the efficiency of the active orthosis increases as tremor power increases. A statistical analysis has been made to characterize the tremor suppression. The statistical analysis has been made using R. A second order polynomial fit has been made with the natural logarithms of power spectra in free and suppression mode. This method allows us to identify a lower limit for efficient tremor suppression; this limit is roughly 0.15 rad^2/s^3. It is mainly related to the interface of the orthosis with the uppper limb since stiffness between the orthotic device and the body is a key factor to control a dynamic process such as tremor. Therefore the characteristics of the transmissions through the soft tissues play an important role in the efficiency of tremor suppression.

Figures 3a and 3b illustrate the effects of WOTAS in the tremorous movement when operating in suppression mode in one patient with a severe tremor. Figure 3a shows the time series corresponding to the tremorous movement of the wrist joint during the arm-outstretched task of one patient exhibiting a severe essential tremor. The top part of the figure shows the time signal with WOTAS in the monitoring mode (left) and in the damping mode (right). Notice that the amplitude of tremor is clearly lower in the damping condition as compared to the monitoring mode. Bottom panels illustrate the same reduction in the frequency domain. The Power Spectrum Density (PSD) has been obtained from the part of the signal with detectable tremor. A clear peak of tremor activity close to 6 Hz is identified. The peak of energy corresponding to the tremorous activity when WOTAS is operating in suppression mode presents a clear reduction. The reduction of the power spectral density (PSD) was 80.4 % in this patient. Notice that the dominant tremor frequency is stable despite of the reduction in its amplitude. Figure 3b illustrates a similar phenomenon for the elbow. Figures 3c and 3d show the effects of the active orthosis on the kinetic tremor associated with finger-to-nose test. A strong reduction in tremor was also observed.

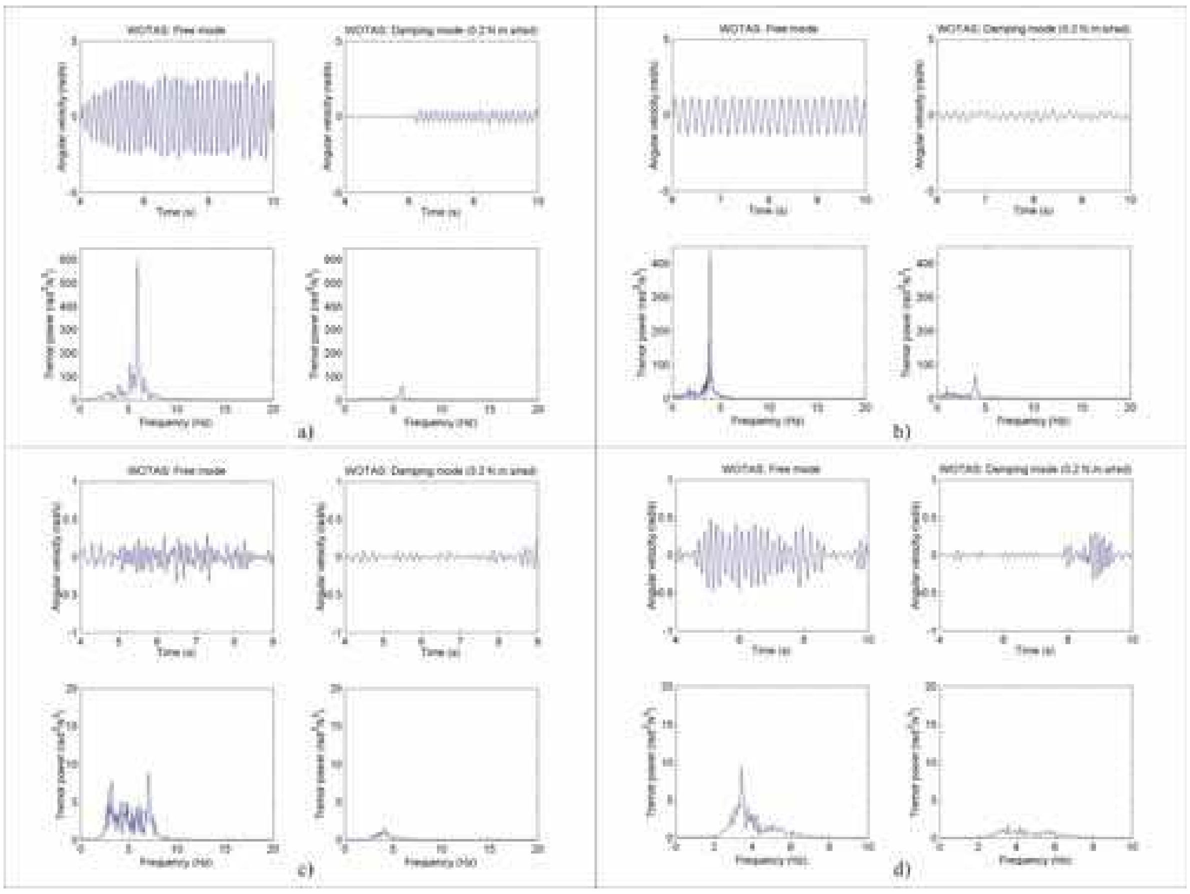

Fig. 3. This figure illustrates the oscillations of the wrist with the associated power spectral density (PSD) of tremor with the motor in a free mode (left panels) and providing viscosity of 0.2 Nms/rad (right panels) in one of the patients. Note the strong reduction in the PSD when viscosity is applied. Oscillations are expressed in rad/sec and PSD is expressed in rad²/s3. a) Reduction of postural tremor of the wrist with WOTAS, b) Reduction of postural tremor of the elbow with WOTAS, c) Reduction of kinetic ("intention") tremor at the elbow with WOTAS, d) Reduction of tremor at elbow level in a patient performing a finger-to-nose task.

Results indicated that the device could achieve a consistent tremor power reduction of 40 % for all patients, being able to reach a reduction ratio in the order of 80% tremor power in determined joints of patients with the most severe tremor. In one patient, the reduction of tremor in the wrist and elbow was associated with a possible rise in tremor intensity at the shoulder level. However, in the majority of patients there was no visible displacement of tremor movement from distal to proximal joints. We call this phenomenon DPTS (distal to proximal tremor shift). The authors believe that it is important to investigate and define the profile of the users who might be affected by this new phenomenon.

There are hints that the mechanical suppression of tremor could produce a "positive" feedback to essential tremor patients. Patients reported that when they realized that the orthosis was suppressing tremor they felt more and more confident to accomplish the task. This behaviour has been detected in patients with severe tremor and requires further research to be confirmed and investigated in-depth.

Overall, patient tolerance was good. No lesions were observed on their skin, expect for a moderate and transient change in skin aspect due to the orthosis. A slight discomfort was reported by some patients. These results suggest this new technique as a possible therapy for tremor suppression in human disorders characterized by postural/kinetic tremor in upper limbs. It opens possible perspectives for disabling forms of tremor, such as tremor encountered in cerebellar and/or brainstem disorders.

3. Enabling technologies

The history of robotics is one of ever closer interaction with the human actor. Originally, robots were only intended for use in industrial environments to replace humans in tedious and repetitive tasks or in those requiring high force and precision, but the current scenario is one of transition towards increasing interaction with the human operator. This means that interaction with humans is expanding from a mere exchange of information (in teleoperation tasks) and service robotics to a close interaction involving physical and cognitive modalities.

It is in this context that the concept of Wearable Robots (WRs) has emerged, (Pons, 2008). Wearable robots are person-oriented robots. They can be defined as those worn by human operators, whether to supplement the function of a limb or to replace it completely. Wearable robots may operate alongside human limbs, as in the case of orthotic robots or exoskeletons, or they may substitute for missing limbs, for instance following an amputation. Wearability does not necessarily imply that the robot is ambulatory, portable or autonomous. Where wearable robots are nonambulatory, this is in most instances a consequence of the lack of enabling technologies, in particular actuators and energy sources. Of the different wearable robots, exoskeletons are the ones in which the cognitive (information) and physical (power) interactions with the human operator are most intense.

In most instances technologies are the limiting factor in developing novel robots. This is also true of wearable robots. Wearable robots are in many cases related to portable and ambulatory applications; however, only a few examples of fully portable wearable robots can be found in the literature, one reason being a lack of enabling technologies.

Ambulatory scenarios require compact, miniaturized, energetically efficient technologies, e.g. control, sensors and actuators. All technologies involved in robotics need further development, but actuators and power sources are the ones that probably most limit wearability and portability at the present time while sensors are the ones most limiting efficient implementation of cHRI, as described in previous section with WOTAS exoskeleton.

In the area of rehabilitation wearable robots, the key idea is empowering a weak musculo-skeletal system or a person with deficient motor control. Functional Electrical Stimulation (FES) becomes an ideal actuation alternative as it uses the muscular system of the user as actuator.

In this context, the authors are collaborating with the European project TREMOR, that tries to overcome the limitations of WRs by exploring the concept of controlling human upper limb muscles as actuators of a Brain computer interface BCI-based system for selective tremor suppression. The final result of the project will take the form of an active garment usable in activities of daily living (ADL). The next sections introduce the main technologies identified by the authors as the ones that will enable the constructions of the next generation of Wearable robot for rehabilitation. First, the use of human muscles as actuators in the pHRI is discussed. Afterwards, exploitation of biological information for the cHRI is presented. This considers both central and peripheral nervous activity, and the resultant motion.

3.1 FES techniques

FES consists in directly activating muscles by stimulating motoneurons and/or triggering reflexes by stimulating sensory nerve fibres. The regulation of the strength of a motor response is controlled by current rate and charge delivered to the sensory-motor systems, (Popovic et al., 2000). FES has been implemented in a wide range of applications: development of neuroprostheses (e.g. for gait restoration, shoulder rehabilitation) paraplegic standing-up (Riener et al. 1998) and walking, correction of drop foot, control of arm movements, or restoring hand grasp function are some examples of FES research.

The already existing FES systems also have some important drawbacks that TREMOR project expects to overcome, namely, muscular fatigue and both discomfort and painful sensations while muscles are being stimulated. Furthermore, the control of the stimulators is not intelligent enough to achieve integration into the natural motor regulation.

TREMOR concept proposes a new methodology for FES, based on arrays of electrodes which overcome the limitations of current electrodes for functional stimulation. In addition it will allow a more selective stimulation of muscles. To achieve this, an innovative addressable electrode array system will be implemented as a new approach to diminish fatigue, (Popovic-Bijelic et al., 2005). Moreover, this FES array is expected to improve comfort and reduce pain due to current distribution. This would be an important advance for FES in general and would go in the direction of minimizing the electrodes to locate on the subject, in order to enhance the wearability of the system. A feasible model of the upper limb musculoskeletal system, allowing to establish dynamic configurations of muscle recruitments that (theoretically) generate the expected compensatory output, would be beneficial for the real-time application of selective artificial muscle activation.

Moreover, our methodology is expected to establish the basis for the development of so-called Soft Robots (SRs). Soft Robots are wearable robots that rely on biological information to interpret both state and intention of the user, and take advantage of his muscles as actuators. There are some challenging issues related to this approach. Regarding at the physical interaction, selective stimulation and control of force must be assured in order to create performing rehabilitation garments.

Impedance Control has been extensively used within the rehabilitation robotics field. TREMOR project aims at creating an easy-to-test platform to validate upper limb impedance control strategies implemented with FES techniques. Consequently, inverse dynamic musculo-skeletal upper limb models will be provided. Regarding at the state of the art, several inverse dynamic models for the generation of motor commands relying on attested muscle models such as Hill's, have been proposed (Riener et al., 1998, Makssoud et al., 2004).

Figure 4 summarizes a preliminary model of elbow control based on activation of the two antagonist muscle groups acting on it, namely biceps brachi and triceps brachi. Real data of a Parkinsonian patient is employed. The proposed model considers the biomechanical characteristics of the upper limb and the current orientation of the arm, and takes as input the EMG activity of both muscles. The EMG-driven Hill muscle model consists of a series elastic element, a contractile element, which is capable of contracting when stimulated either naturally or by means of FES, and a passive spring in parallel to them, and is based on (Zajac, 1989, Lloyd et al., 2003). Muscle lengths and their ratio of variation, which define force-length and force-velocity contributions of each muscle, are obtained with a regressive model that relates normalised muscle lengths with joint flexion angles, (Hawkins et al., 1990). Satisfying results are obtained.

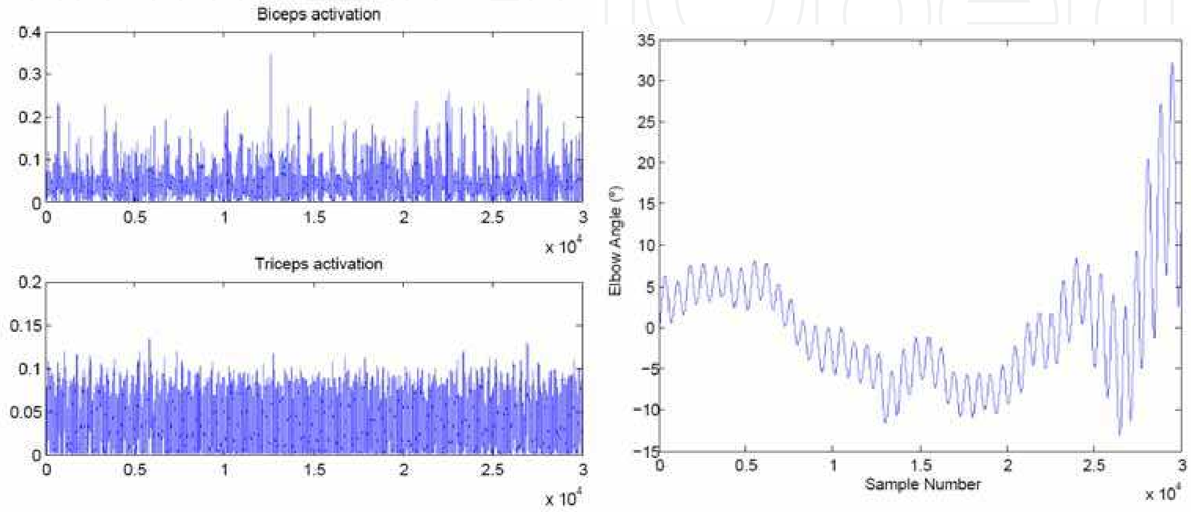

Fig. 4. This figure shows the resultant elbow angle (right) based on rectified biceps and triceps EMG activity (right). EMG signals were acquired at 3008 Hz. A 90º angle between the arm and forearm is considered as reference (0º). Forearm motion has the same frequency than the one measured by piezoelectric accelerometers attached at the distal part of the forearm, and shows an increase in tremor amplitude due to a posture change.

This model sets the basis for the development of inverse models for a 3D scenario that envisage the presence of non-predictable external forces. These will be one of the contributions of the TREMOR project: controllable (i.e. real-time feasible), three-dimensional, upper limb joint models. They will account of non planar movements and will strengthen the physiological congruity in the FES field by including fatigue in the dynamic representation.

3.2 Inertial sensing technology

MEMS inertial sensors are suitable for tracking changes in velocity, position and orientation. In the past, accelerometers have been built with large mechanical masses and gyroscopes with multiple mechanical gimbals and bearings. Recent advances in microelectromechanical system (MEMS) technologies have made miniaturized inertial sensors possible. These devices are currently an exciting alternative to motion capture in wearable applications. In particular, accelerometers have been judged suitable for compensation of user motion, e.g. in closed loop configurations for wearable vision platforms, (Mayol et. al., 2000), or tremor compensation in instruments for microsurgery, (Riviere et al., 1995). Examples of applications of rate gyroscopes include active compensation of upper limb tremor by means of motorized exoskeletons, (Rocon et al., 2007), control and monitoring of leg orthoses, (Moreno et al., 2006), and others.

In the framework of TREMOR project recording of upper limb movement with IMU sensors aims at two goals. First, IMU sensors will provide the orientation of each segment based on a sensor fusion approach that merges accelerometer and gyroscope information using a Kalman filter. This will serve as an input for the calculation of the current muscle length and velocity, which are required by the inverse musculo-skeletal models. Second, two IMUs placed at the distal and proximal segments of a joint will provide directly its angular velocity, (Rocon et al., 2006). On the basis of this, a two-stage algorithm for estimation of instantaneous tremor frequency and amplitude has been developed as described below.

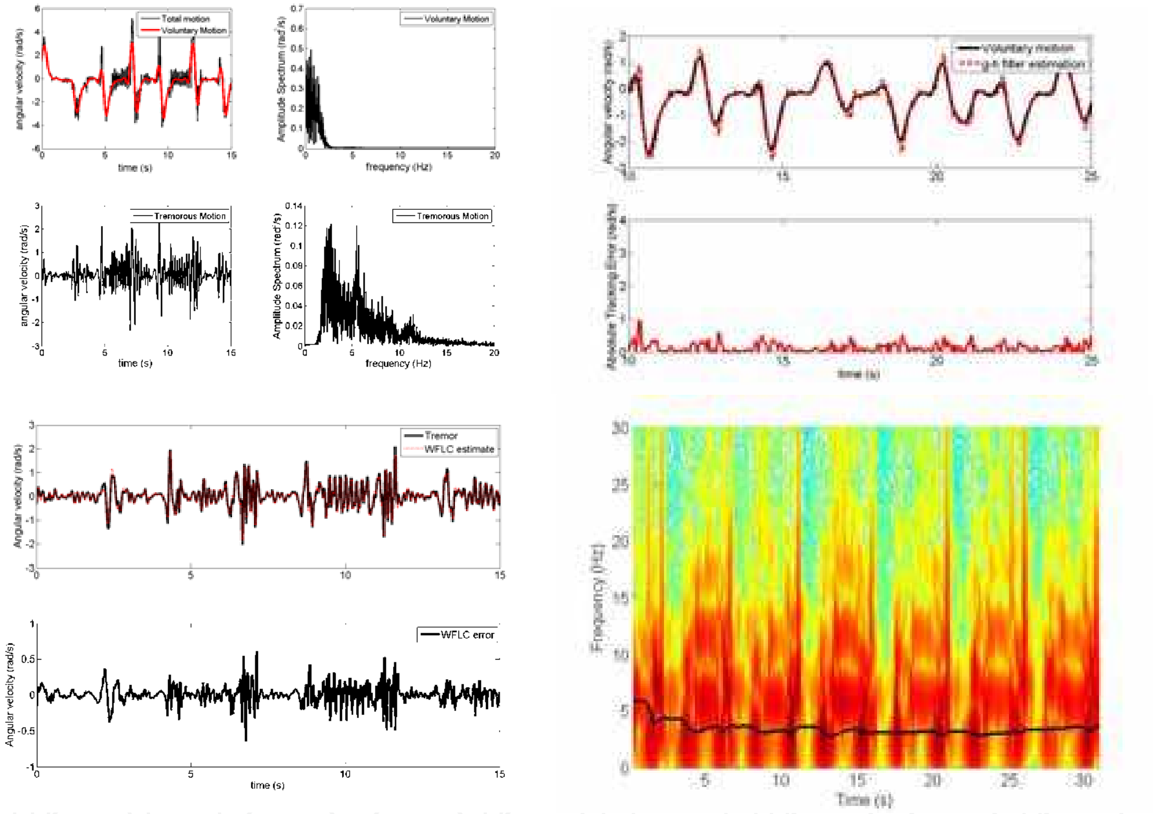

Fig. 5. Top left: Example of application of the two stage algorithm: Voluntary and tremorous motions are estimated based on their different frequency content. Top right: Voluntary motion estimation for the wrist recording of a tremor patient by means of a critically dampened filter and its estimation error. Bottom left: tremor estimation for the wrist joint obtained with the WFLC and estimation error. Bottom right: amplitude spectrum of the tremor recording and WFLC tremor frequency estimation.

It has been demonstrated that tremor happens at higher frequency than voluntary motion (Mann et al., 1989), and that affects it in an additive manner, (Riley et al., 1982). Therefore, voluntary motion estimation can be thought of as a tracking problem where tracking of slow dynamics of total movement is desired. Subtracting an accurate estimation of voluntary motion to the overall recorded movement provides directly the “isolated” tremor signal, Fig.

5 (top left). This tremor estimation is fed into an adaptive algorithm, which calculates its amplitude and frequency.

Voluntary motion tracking based on g-h filters and a Kalman filter is evaluated. Based on data from a group of patients suffering the major tremor disorders, it is concluded that the critically dampened filter (Brookner, 1998), a special type of g-h filter, provides the best performance, Fig. 5 (top right). Once this voluntary motion estimation is subtracted from the overall movement, a tremor estimate is directly generated. Instantaneous tremor amplitude and frequency are obtained with the Weighted Frequency Fourier Linear Combiner (WFLC), which continuously adapts a time-varying Fourier series to the input signal (Rivere, 1995). The WFLC is based on the Least Mean Square method, a gradient descent-like approach, (Widrow et al., 1985). Figure 5 (bottom left and right) demonstrate the performance of the WFLC as both amplitude and frequency tracker for a recorded wrist tremor signal.

3.3 BCI and the context of tremor identification, characterization and tracking

BCIs can be considered as any means that makes it possible to create a direct communication pathway between the human nervous system and any external device. This definition encompasses a broader term than that generally considered as coming from the original acronym, which is Brain Computer Interface: as a matter of fact, BCI has been recently re-phrased as the acronym for Brain Controlled Interface, (Schwartz et al., 2006), thus enclosing any kind of device which might be controlled by the brain, such as a speech synthesizer, any assistive appliance, and neural prostheses, (Mason & Birch, 2003).

Results obtained in the last years in this context enlightened the possibility of using interfaces that can non-invasively provide non-muscular communication and control for people with severe motor disabilities, including ALS patients, (Sellers & Donchin, 2006), stroke survivors, (Dobkin, 2007), and SCI subjects, (Boord et al., 2004). In fact, despite the increasing number of experiments in the context of BCI denounces the interest in the area of assistive technology, results in controlled environments are still somewhat contradictory, and render the applicability of the techniques devised up to now still unpopular.

One of the reasons that may justify this has been recently singled out by considering the physiological principle of combination and distribution of roles in the planning and execution of movements in humans, (Wolpaw, 2003): motor outputs are obtained by a blend of activities of different areas including not only the relevant CNS areas. By adopting a "goal selection" strategy, and then limiting the BCI to give reliable information on user's goal, and let another structure to work on the lower aspects, the variability in performance of BCI-based systems can be reduced. Following this perspective, BCI-based systems need to be complemented with several kinds of information ranging from central to peripheral motor structures.

The second limitation resides in the intrinsic difficulty of classifying different intended movements or actions by using a limited number of EEG electrodes. This at present limits the reconstructed flow of information at around 25 bits/min (i.e. resolving 25 binary answers every minute), (Wolpaw et al., 2002). As a matter of fact, if in controlled environments and with trained subjects it is at present possible to reveal the intention to move, and discriminate between e.g. four directions to drive a cursor or a wheelchair, (del Millán, 2003), having an interface solve complex and functional tasks such as grasping a glass, or handling a fork is still a challenge.

Moreover, the development of interfaces based on EEG electrodes raises functional operational issues:

1. Placement of the acquisition system on the user requires the assistance of a trained carer.
2. The process requires a time consuming and costly training process for EEG classifiers.
3. The robustness is still low due to quality and variability of the EEG signal. Some of the factors influencing negatively robustness are: noise and artifacts, long-term interface stability (long-term stability here meaning a matter of hours), drying of the electrolytic contact gel, fatigue, hormone levels, the time of day, the environment itself, etc. These factors can influence the signal negatively, resulting in patterns that the interface algorithms have difficulty in recognizing.

But if the challenge coming from the complexity of functional movements hasn't been solved yet, the possibility to combine EEG signals and other source of data to minimize perturbations (e.g. essential tremor, dyskinesia) to the desired movements is a more manageable effort. In this context, some new findings have been reported: it has been indeed verified that, for instance, muscular tremor is proxied and predicted at the cortical level of the contra-lateral side, (Hellwig et al., 2001), with time delays of some tens of ms, (Raethjen et al., 2000), (this has been quantified by using isocoherence maps between EEG and EMG). This sets the basis for the possibility of adding reliable and timing information on the onset of tremor at the peripheral level, by acquiring EEG data in combination with signals acquired at the peripheral level.

The detection of tremor contribution on EEG signals together with the one of voluntary movement, which is typical of all the classical BCI studies and is gathered by the depression of μ and β bands, can be used as a further input for algorithms dealing with the tremor detection. In this case, the multimodal BCI would rely on EEG, EMG, and IMU data to be combined together to 1) determine movement intent and initiation, 2) predict and reveal the presence of tremor, and 3) provide a real-time estimation of time-varying characteristics (amplitude and frequency) of this tremorous movement.

Over the last years, many research efforts have been focused on the fusion of the information from several different sensors technologies, e.g. EEG, EMG and inertial (gyroscopes and accelerometers). The main focus of this research is on the study of: synchronisation between muscle and the motor cortex activity, coupling in muscles and detection of oscillators, (Manto et al., 2003). EMG contains rich information that can be used to recognise neuromuscular activity in a non-invasive manner. Under normal conditions, muscle contraction is activated by the motor cortex. The control signals flow from the CNS to the PNS, finally reaching the muscle tissue. Electromyography is the study of the potentials generated during muscle contractions. The acquired EMG signal is usually considered to be random. Extracting information from EMG signals is not trivial. Many models have been proposed for surface EMG (sEMG), e.g. the Anvolcon model, (Blok et al., 1999), the EMGsim model, (Farina et al., 2001), the RRDsim model, the SiMyo model, (Duchene & Hogrel, 2000), and the Fuglevand model. However, these models do not include all the factors that affect EMG signals, such as electrode configuration and location, fibre type, blood flow, subcutaneous tissue, skin preparation, signal conditioning electronics, processing techniques and others. In the sEMG for Non-Invasive Assessment of Muscles

(SENIAM) project, most of the above-cited models were analysed and the limitations of each model discussed, (Hermens et al., 1999).

The EMG sensors not only measure mechanical limb tremor. The signals contain a broader spectrum of the muscle excitation patterns. This is an advantage of EMG as compared to inertial sensors. However, most of the methods applied to process EMG signals require certain assumptions like stationarity of the involved process. Sudden oscillators causing tremor can appear under certain conditions violating the stationarity principle. Fatigue-induced tremor is an example of time dependent tremor, (Brunetti et al., 2007).

Many research projects have used EMG to enable Human Machine Interfaces, (Ferris et al., 2006). As in EEG, the development of interfaces for wearable devices based on EMG electrodes raises operational issues, (Pons, 2008):

1. The measurement of the muscle activity is sensitive to the placement of the electrodes on the user.
2. The selectivity of the measurement is low since the acquired signal is usually considered to be random. The extraction of features from the signal requires complex models.
3. EMG-based systems usually require a learning and training process from the user.
4. The measurement of an EMG sensor could be influenced by FES electrodes.

TREMOR project aims at implementing a BCI-based detection, identification, characterization and tracking system to provide information on tremorous and voluntary motion and will allow us to be selective in the application of FES forces on only tremorous motion.

4. Discussion and conclusions

Wearable Robots (WR) may set the basis for new rehabilitation techniques. All technologies involved in robotics need further development, but actuators are the one that probably most limit wearability and portability at the present time while sensors are the most limiting efficient implementation of cHRI and pHRI.

This paper introduces WOTAS, a wearable exoskeleton able to attain a reduction ratio in the order of 80 % tremor power in specific joints of patients with severe tremor. The work presented validated the concept of tremor suppression by means of biomechanical loading. Nevertheless, the approach to mechanical suppression of tremor by means of orthotic devices presents limitations mainly due to the physical interaction between the exoskeleton and the human limb:

1. The transmission of forces through soft tissues plays an important role in the efficiency of tremor suppression. There is a physical limitation for tremor suppression through wearable devices due to force generation (size and power consumption of the actuators) and transmission through soft tissues.
2. Despite the success of the approach, there is no suitable actuator technology in terms of cosmetic and aesthetic (low weight, compact to be worn beneath the clothes) as well as functional requirements (torque, bandwidth).
3. Patients related that these bulky exoskeletons could not be considered as a solution to their problem since it is considered that the use of such device should cause social exclusion.

In summary, robotics based solutions have shown clinical evidence of the approach based on human limb impedance control. However it results in bulky and non cosmetic solutions for which patients are especially reluctant. Based on these results, authors of this book chapter identified the main limitations of the current technology used on wearable robots. In section 3, authors identify the technologies that will pave the way for the next generation of wearable robots. The use of the identified techniques is presented in the framework of the European project TREMOR.

Human muscles can be set as actuators of a wearable robotic systems. The integration of FES systems within WRs techniques over a textile sustrate will allow the creation of Soft Robots. Soft Robots are wearable robots that rely on biological information to interpret both state and intention of the user, and take advantage of his muscles as actuators. In this context, TREMOR project aims at the development of biomechanical models of human muscles under FES, in order to obtain optimal (in the senses of fatigue minimization and improvement of confortcomfort) stimulation patterns. Also an individually addressable, multielectrode FES array will be developed in order to obtain dependable and safe actuation at the pHRI.

The BCI in the context of tremor suppression must identify high-level mental states that reflect a user's desire to convey information. For this, the BCI device is defined to translate direct measures of brain activity into messages or commands to the soft robot and provide the user with real-time feedback. This BCI can also include systems that rely on passive monitoring, information derived from the peripheral nervous system and indirect measures of neural activity, such as EMG

Acquisition of bioelectrical information can be complemented with recording of actual motion by means of IMU sensors. IMU sensors provide an ambulatory, wearable means of recording limb kinematics, and, in the case of TREMOR project, serve to estimate the state of the musculo-skeletal system and to characterize tremor at joint level.

5. Acknowledgments

The work presented in this paper has been carried out with the financial support from the Commission of the European Union, within Framework 7, specific IST programme "Accessible and Inclusive ICT", Target outcome 7.2 "Advanced self-adaptive ICT-enabled assistive systems based on non-invasive Brain to Computer Interaction (BCI) ", under Grant Agreement number ICT-2007-224051, "TREMOR. An ambulatory BCI-driven tremor suppression system based on functional electrical stimulation."

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Rehabilitation Engineering
Edited by Tan Yen Kheng

ISBN 978-953-307-023-0
Hard cover, 288 pages
Publisher InTech

Published in print edition December, 2009

Population ageing has major consequences and implications in all areas of our daily life as well as other important aspects, such as economic growth, savings, investment and consumption, labour markets, pensions, property and care from one generation to another. Additionally, health and related care, family composition and life-style, housing and migration are also affected. Given the rapid increase in the aging of the population and the further increase that is expected in the coming years, an important problem that has to be faced is the corresponding increase in chronic illness, disabilities, and loss of functional independence endemic to the elderly (WHO 2008). For this reason, novel methods of rehabilitation and care management are urgently needed. This book covers many rehabilitation support systems and robots developed for upper limbs, lower limbs as well as visually impaired condition. Other than upper limbs, the lower limb research works are also discussed like motorized foot rest for electric powered wheelchair and standing assistance device.

How to reference

E. Rocon, J.C. Moreno, J.A. Gallego and J.L. Pons (2009). Wearable Robots in Rehabilitation Engineering Tremor Suppression, Rehabilitation Engineering, Tan Yen Kheng (Ed.), ISBN: 978-953-307-023-0, InTech, Available from: http://www.intechopen.com/books/rehabilitation-engineering/wearable-robots-in-rehabilitation-engineering-tremor-suppression

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